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DESIGN PARAMETERS AFFECTING THE ACCURACY OF ISOTHERMAL THERMOCOUPLES

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Accuracy	Askew Installation	Tungsten/Rhenium
Wire Diameter	Trajectory	
Insulation Thickness	Heatshield Material	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents an analytical study of the isothermal thermocouple commonly used on ballistic reentry vehicles to obtain the flight test data necessary to determine the thermodynamic performance of the heatshield. The objective of this study is to investigate the thermocouple design parameters and techniques that contribute to the instrument's accuracy. These parameters include the thermocouple wire diameter, the isothermal length, the lead wire length, the electrical insulation thickness, the type of heatshield material, the thermocouple depth, and the interference effects in multiwire plugs.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

Introduction

The isothermal thermocouple has been used since the mid 1960s on various ballistic reentry vehicle programs. A typical isothermal thermocouple is shown in Fig. 1, where the horizontal segment of the thermocouple wire is called the isothermal length, and where the vertical segment is called the lead wire length. When more than one thermocouple is installed in a plug, the overall assembly is called a multiwire thermocouple plug. The purpose of this design is to minimize the error due to heat "leakage" from the hot junction by conduction down the sides through the lead wires. The longer the isothermal wire length, the smaller the error. The magnitude of the error is a function of the differences in conductivity between the heatshield material and the thermocouple material, the isothermal wire length, the wire diameter, the lead wire length, the installation, etc. In [1],[1] the magnitude of the error due to the differences in thermal conductivity between the thermocouple wire and the heatshield was shown to be as high as 50 percent for the post (or bayonet) thermocouples. A post thermocouple is essentially a straight pair of wires inserted into a heatshield per Fig. 2.

As discussed in [2], the isothermal thermocouple is the most accurate thermocouple used to measure the temperature history of a ballistic reentry vehicle heatshield with correlations between the predicted and measured flight test data approaching ±5 percent of the

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[1] Numbers in brackets designate references at the end of this report.

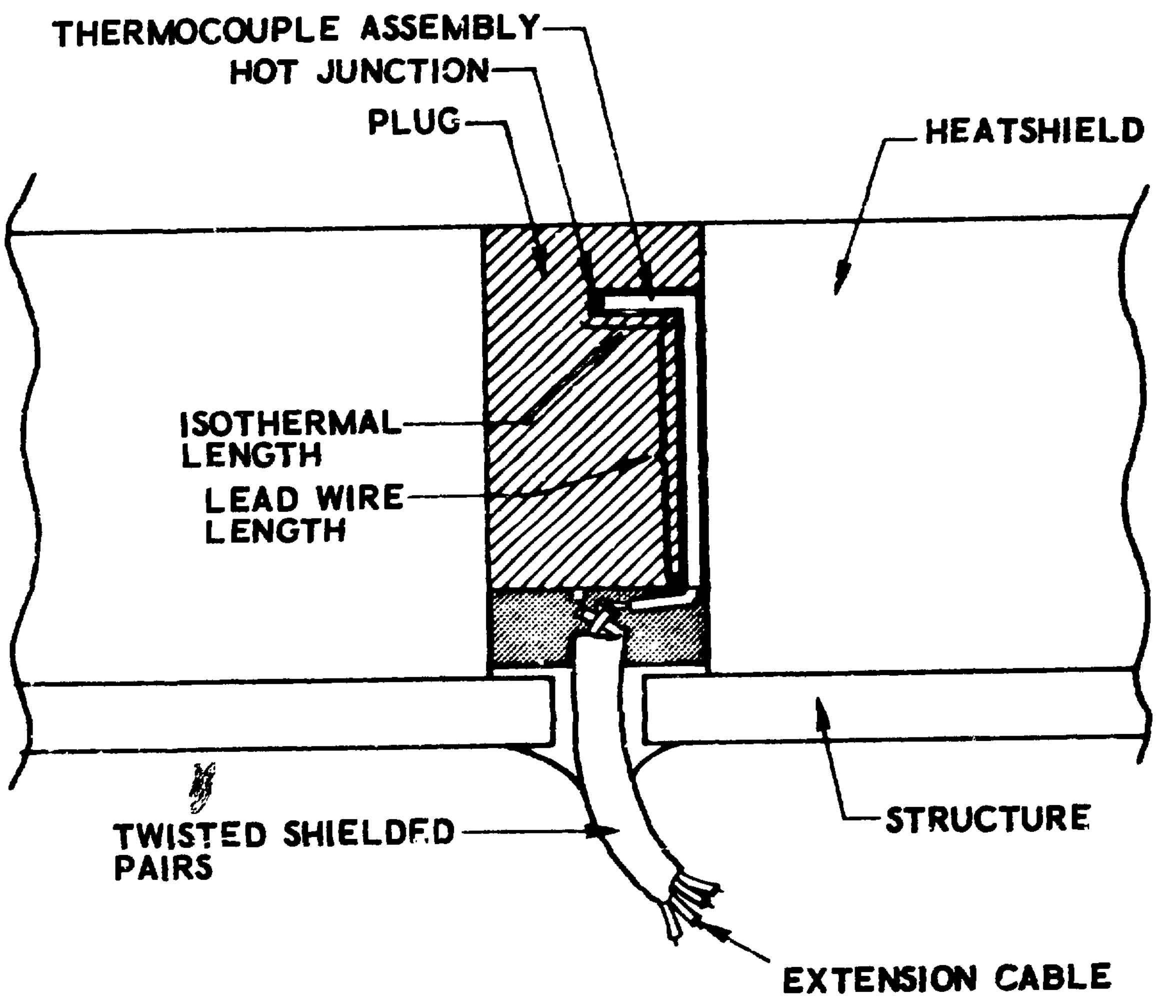


Fig. 1 Isothermal Thermocouple Installation

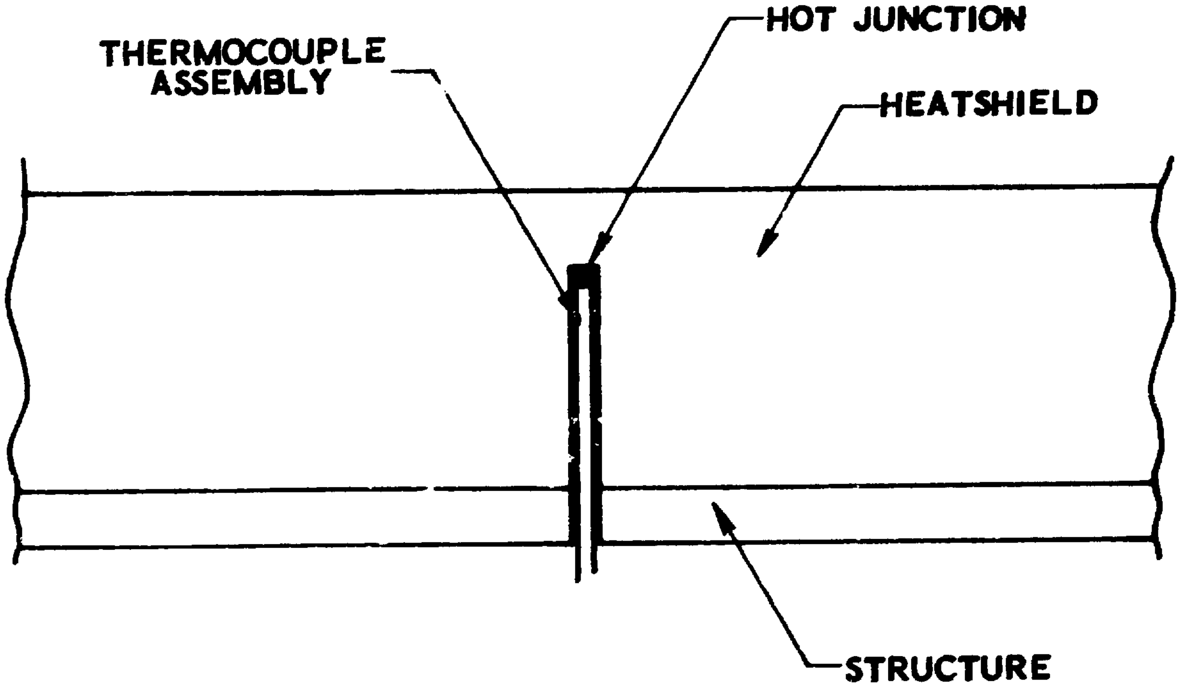


Fig. 2 Post Thermocouple Installation

actual value. Reference [2] recommends that a series of tests be run in a ground facility to determine optimum lead wire diameter, isothermal wire length, wire insulation thickness, and various design expedients to improve the performance of the isothermal thermocouple.

This report endeavors to predict analytically the effects, or trends, of the following on the accuracy of the multiwire isothermal thermocouple plug assembly commonly used on ballistic reentry vehicle programs:

1) Wire diameter
2) Lead wire length
3) Isothermal length
4) Electrical insulation thickness
5) Thermocouple depth
6) Common heatshield materials
7) Trajectory
8) Askewness in installation and installation depth accuracy
9) Potting compound
10) Interference effects from multiwire thermocouple installations on each other

The three types of thermocouple wires commonly used during the past decade in isothermal thermocouples were tungsten/rhenium, chromel/alumel, and iron/constantan, which covered the 0 to 5000, 0 to 2200, and 0 to 1200°F temperature ranges, respectively. In a typical four-wire isothermal plug, the tungsten/rhenium wires were used in the two positions nearer the heatshield outer surface, while the chromel/alumel and iron/constantan wires were used in the two positions farthest away from the heatshield surface, respectively. It has happened on numerous occasions that the range of chromel/alumel and iron/constantan thermocouples was too low for the thermocouples to measure the temperature history attained by the heatshield; consequently, a quantity of valuable flight test data was lost. The current trend is to use tungsten/rhenium wire thermocouples at all four positions in the plug. Therefore, only the tungsten/rhenium wire will be considered in this study. Specifically, the thermocouple wires considered are tungsten-26 percent rhenium/tungsten-5 percent rhenium (W26Re/W5Re)

Analysis Model

In the single and multiwire configurations the isothermal thermocouple plug assembly was simulated with the [3] computer program, which is a lumped parameter type, and is known in the aerospace industry as a "thermal analyzer type" computer program. This computer program simulates a physical system as a finite number of small elemental volumes with their associated thermal capacitances connected in one-, two-, or three-dimensional arrays via thermal resistances. A more detailed discussion of the Thermal Analyzer computer program [3] to this application is provided in Appendix A. Considering the computer and the computer program limitations with respect to computer time costs, data storage capacity, and program dimensions, this simulation was limited to two dimensions. This simulation did not account for all of the ablative processes involved in a reentry vehicle ablative heatshield. However, for temperatures up to 1200°F, the procedure of [4] to deduce heatshield thermodynamic properties from flight test data showed that the [3] computer program was adequate. In order to include all of the ablative processes involved in an ablative heatshield, a Charring Ablator computer program similar to [5] with multidimensional capability ([5] does not have the multidimensional capability) combined with the Thermal Analyzer computer program [3] would be required. Such a combined program was not available at the time of this study, thus the Thermal Analyzer computer program [3] was used.

The accuracy of this simulation is greatly dependent upon the length of the thermocouple plug and of the thickness of heatshield being simulated. For example, the temperature gradient in a 0.25-in.

carbon phenolic plug will be higher than that of an adjacent 0.25-in. carbon phenolic heatshield that is bonded to a 0.125 in. thick aluminum substructure for a typical 23,000 fps, 40-deg reentry angle trajectory, because of the higher conductive heat transfer from the thin heatshield into the aluminum substructure than is radiated from the backface of the plug into the vehicle interior. For a plug and/or a heatshield on the order of 0.75 in., the temperature gradients would both be identical for the same trajectory, because 0.75-in. carbon phenolic presents an infinite slab conduction solution for most common trajectories. Most contemporary ballistic reentry vehicle heatshield thicknesses vary between 0.2 and 1.0 in. An example of the relationship between model accuracy and heatshield thickness is presented in Fig. 3, where the temperature histories for finite plug slab thicknesses of 0.020, 0.100, and 0.200-in. depths are compared to those at similar depths in a 0.410-in. plug. An adiabatic wall is assumed at the backface of the finite plug slab and the 0.410-in. plug.

In some specific thermocouple plug designs, a potting compound has been applied in a very thick layer to the base of the thermocouple plug, around the connections of the lead wires to the cables that carry the thermocouple millivolt output to the telemetry system. Therefore, the finite slab-adiabatic wall simulation assumption would be correct for these specific designs. The 0.410-in. plug simulation was a simplification of that used for the 0.020, 0.100, and 0.200-in. finite slab solutions. In the finite slab solutions, the heat transfer model included the two-dimensional heat transfer effects of the thermocouple wire and its insulation in the resistances and capacitances of the analog. In the simulations of the 0.410-in. plug, only the

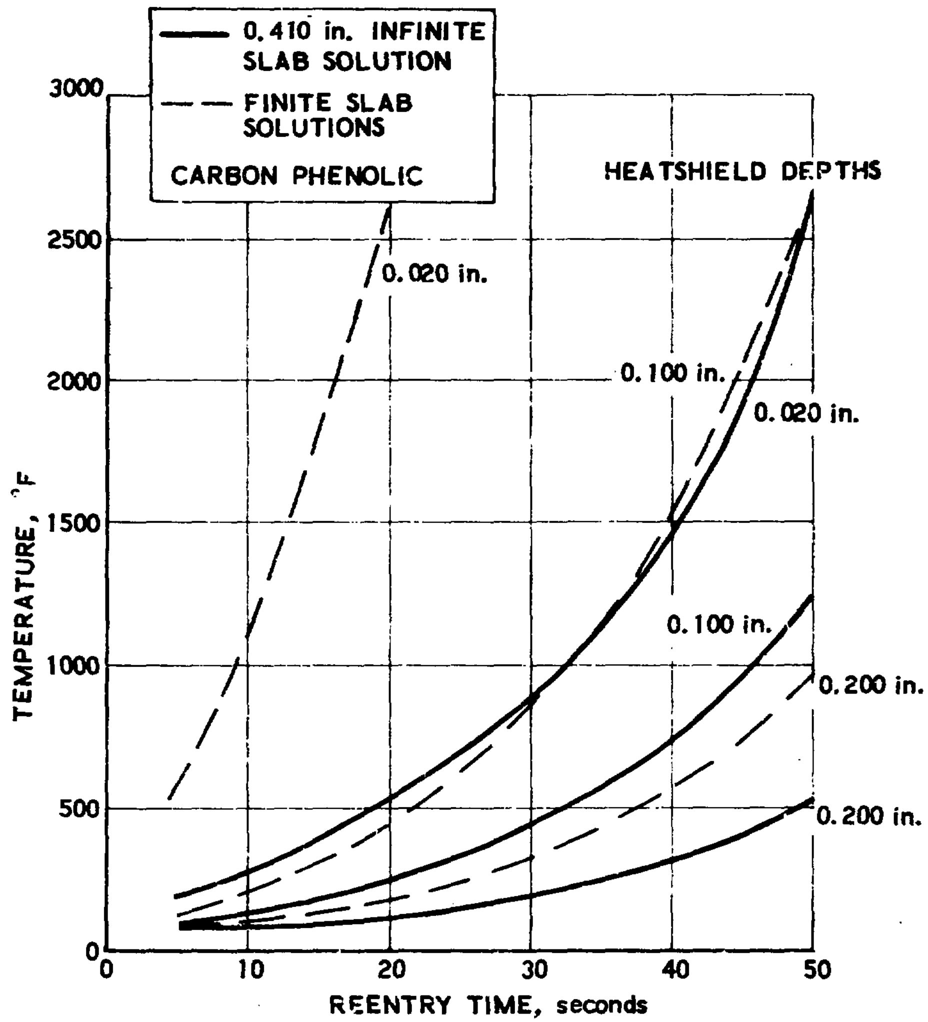


Fig. 3 Infinite Vs Finite Slab Solution

capacitive effects of the thermocouple wire and electrical insulation were considered. Note the large differences in Fig. 3 (up to factors of five in the case of the 0.020-in. depth) in the temperature histories between the finite and the infinite slabs for like depths. These differences decrease with increased depth, to where the maximum temperature history differences at the 0.200-in. depth is, at most, 50 percent of the finite slab solution.

Most of the parameter studies in this report were made for the 0.200-in. finite slab case. The [2] flight test results tend to support the simplified simulation in cases where the predicted and measured flight test data correlated to within ±5 percent of the actual value.

Since each isothermal thermocouple plug manufacturer has a different design and modified manufacturing techniques, a plug model configuration must be selected that will be applicable to as many designs and techniques as possible. For example, one configuration (Fig. 4) shows the junction to be located on the centerline of the plug with a lead wire coming down each side of the plug in a milled channel. A second configuration is shown in Fig. 5 where the junction is located off-center near one edge of the plug, and both lead wires run parallel down the same side. This configuration, incidentally, permits longer isothermal wire lengths per given plug diameter than the configuration in Fig. 4. With these configurations in mind, the following two models based on different assumptions were considered:

1) Assume a minimum channel width that can be milled into a plug and fill the dimensions of the channel with the width requirements of the thermocouple wire and the electrical insulation. Since

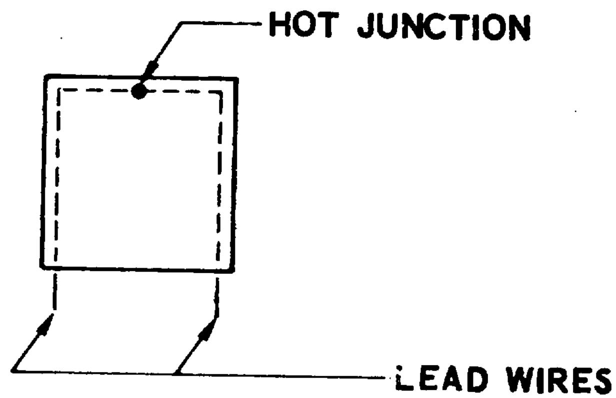


Fig. 4 Isothermal Thermocouple Plug, Configuration A

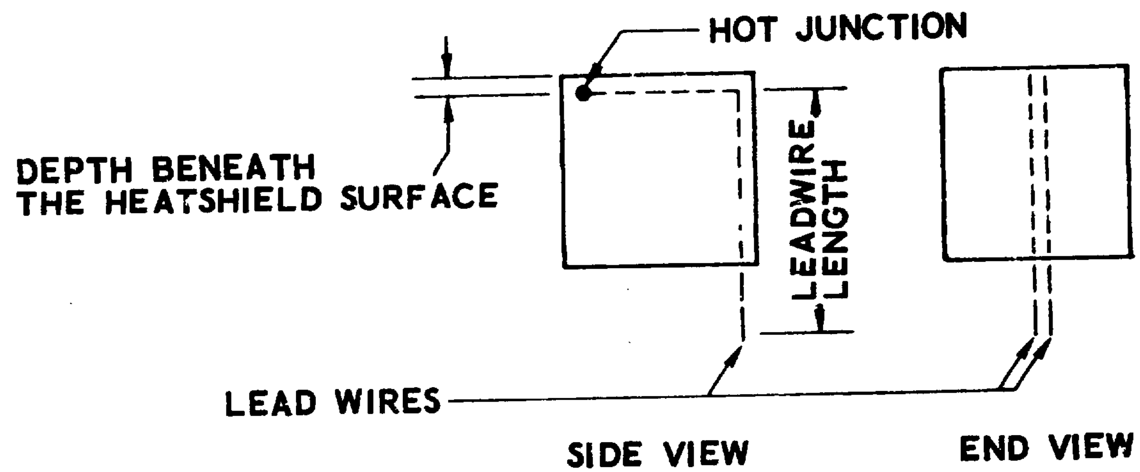


Fig. 5 Isothermal Thermocouple Plug, Configuration B

three wire sizes and three insulation thicknesses were considered in this study, the excess of space in the milled channel will vary, and this would be simulated with an appropriate filler material.

2) Assume the channel width to be equal to the diameter of the wire, plus twice the thickness of the electrical insulation.

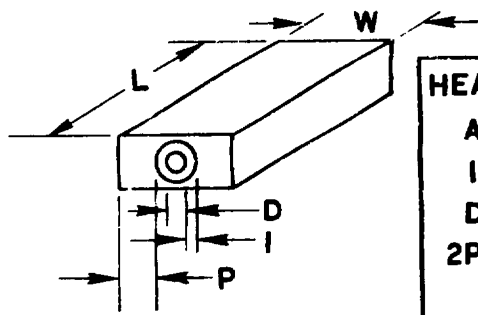
Both models are sketched in Fig. 6, and most of the study was made for both models. However, in actual practice, there seems to be no limit to milling narrow channels so that configuration B in Fig. 6 more nearly simulates some of the plugs currently being manufactured.

As shown in Fig. 7, the differential effects of the Fig. 6A and B configurations on the temperature, as measured by the 0.003-in. thermocouple wires covered with 0.001 in. of boron pyrolytic nitride (BPN) insulation, amounted to about 12 percent at all temperatures relative to the temperatures calculated from the Fig. 6B configuration for a thermocouple located 0.020 in. below the heatshield surface.

Because of the inexactness of the thermal simulation and of the design differences in thermocouple plug manufacture as previously discussed, the results of this study should be regarded in a qualitative sense rather than a quantitative sense. Also, all of the studies, except as noted, were based on an assumed 6-deg angle ballistic reentry vehicle trajectory per the procedure developed in [6].

Another study of isothermal thermocouple accuracy was noted in [7] for multiwire isothermal thermocouple plugs developed for rocket nozzle applications. The [7] study was restricted to the accuracy of the indicated temperature, of the thermocouple electrical output, and of the thermocouple depth location in the rocket nozzle. The first two

A. CONSTANT CHANNEL WIDTH, W



HEAT TRANSFER AREA, A

A = L x W

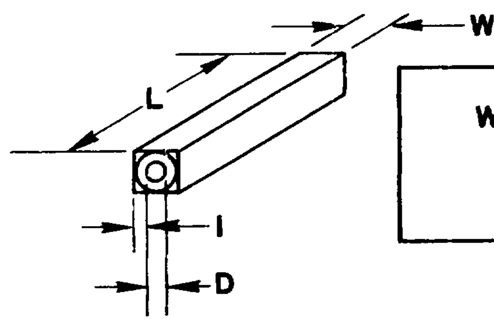
I = INSULATION THICKNESS

D = WIRE DIAMETER

2P = W - (2 I + D), THE REMAINDER OF THE CHANNEL FILLED WITH POTTING COMPOUND

L = ISOTHERMAL LENGTH

B. VARIABLE CHANNEL WIDTH, W



W = 2 I + D

NO WIDTH ALLOWANCES FOR POTTING COMPOUND

Fig. 6 Isothermal Thermocouple Plug Simulations

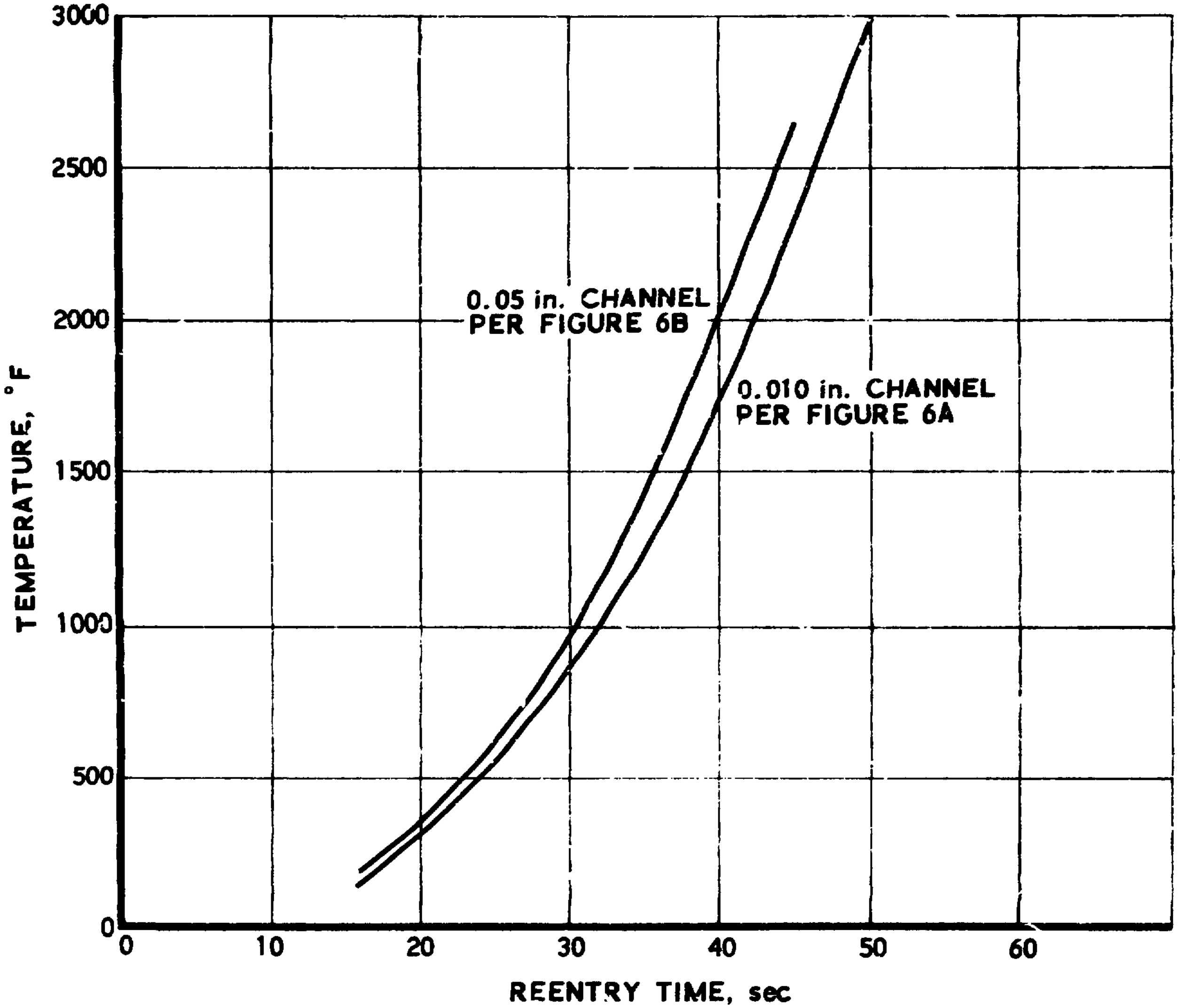


Fig. 7 Channel Simulation Effects on Model Accuracy

items covered aspects of thermocouple accuracy not covered in this report, whereas the accuracy of thermocouple location was studied in both efforts. Also, the plug design in [7] differed from those depicted in Figs. 4 and 5, and the simulation of the thermocouple wire was similar to that presented in this study. The basic computational tool described in [7] attempted to account for some of the ablation process via manipulating the values of heatshield density, specific heat, and thermal conductivity. This same expedient was used in the [3] computer program as for this study. However, this expedient is only considered accurate to about 1000°F for the heatshield materials and applications considered in this study since this is the beginning of the temperature regime where the density of the heatshield materials considered decreases rapidly with an increase in temperature. This density decrease is due to the phenolic resin binder in the heatshield boiling off rapidly at the 1000°F temperature.

In this study and [7], the inability to couple a Charring Ablator computer program [5] to the Multidimensional Conduction computer program [3] is the weakness in both simulations. The varying of the heatshield's specific heat, thermal conductivity, and density to account for the ablative process may cause significant differences in the calculated temperatures for temperatures exceeding 1000°F. Some of the problems associated with the selection of heatshield thermodynamic properties will be discussed in Appendix B.

Wire Diameter Effects

The wire diameter effects on the isothermal thermocouple accuracy were studied for 0.005, 0.003, and 0.001-in. wire. The 0.005-in. diameter wire was used on many of the ballistic reentry vehicles flown during the past decade [2]. Since a thermocouple wire represents a heat sink relative to the heatshield material in which it is inserted, it is obvious that the thermocouple junction will be at a lower temperature than the undisturbed heatshield. It is equally obvious that it is desirable to reduce the mass of the thermocouple as much as possible in order to reduce the temperature difference between the thermocouple junction and the undisturbed heatshield. However, it was assumed that there is a minimum practical limit in thermocouple diameter; therefore, a 0.001-in. wire was the minimum wire diameter selected for this study because it was felt that any thermocouple assembly with smaller wire would be relatively expensive to manufacture. Also, for 0.001-in. diameter wires and smaller, it is feared that small imperfections in the surface (nicks, scratches, etc.) could affect the cross sectional area of the wire sufficiently to degrade the performance of the thermocouple.

As tabulated in Fig. 8, a thermocouple plug made from carbon phenolic was simulated with the W26Re/W5Re thermocouple wires installed at the 0.200-in. depth per the conditions and installations depicted in Figs. 1, 5, and 6B. The isothermal length was 0.200 in. and the lead wire length was 0.500 in. with 0.001 in. of BPN electrical insulation covering the wires. The percentage difference (%D) is the calculated difference between the calculated temperature in the undisturbed heatshield (T_A) and the calculated temperature of the

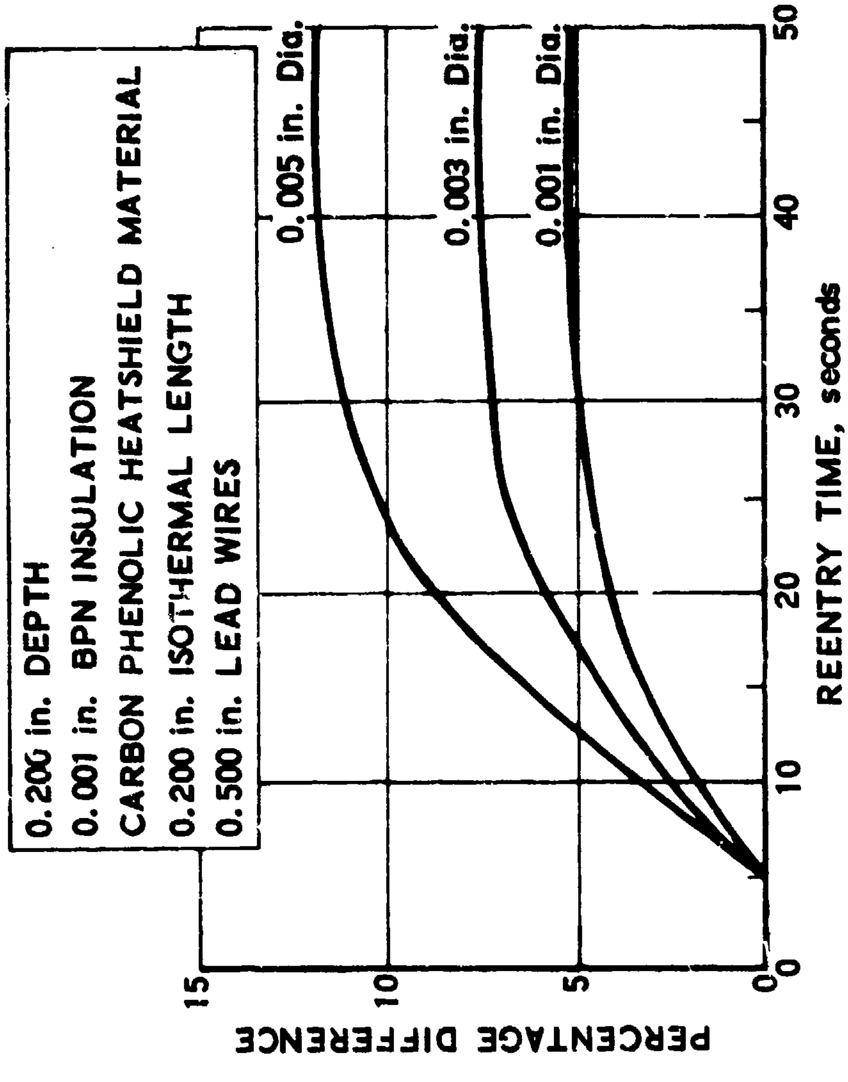


Fig. 8 Wire Diameter Effects

thermocouple junction when it is inserted into the heatshield (T_M), and is referred to as the undisturbed heatshield temperature.

$$\%D = \frac{T_A - T_M}{T_A} \times 100\%$$

This designation of the percentage difference will be used throughout this report. As shown in Fig. 8, the maximum percentage differences for the 0.005, 0.003, and 0.001-in. diameter thermocouple wires were 11.8, 7.5, and 5.2 percent, respectively. Hence, the percentage difference decreased with wire diameter.

The wire size effects study was carried out simultaneously with the electrical insulation thickness and isothermal length effects studies.

The effects of work hardening of the thermocouple wire on the temperature response were not considered in this study. In fact, the calibration curve may change after the wire is bent.

Insulation Thickness Effects

The insulation thickness effects were studied with the same basic configuration as that for the wire diameter effects. The wire diameter was held at a constant 0.003 in. while the BPN insulation thickness was varied from 0.001 to 0.003 in. As shown in Fig. 9, the percentage difference decreases very slightly from 7.5 to 6.3 percent as the BPN insulation thickness increases from 0.001 in. to 0.003 in. Hence, the differential effects on thermocouple accuracy for BPN thicknesses in the 0.001 to 0.003-in. range are negligible; thus, the manufacturer could tolerate this 0.002-in. spread in his BPN wire coating specifications. The accuracy appears to have increased with the increase in insulation thickness.

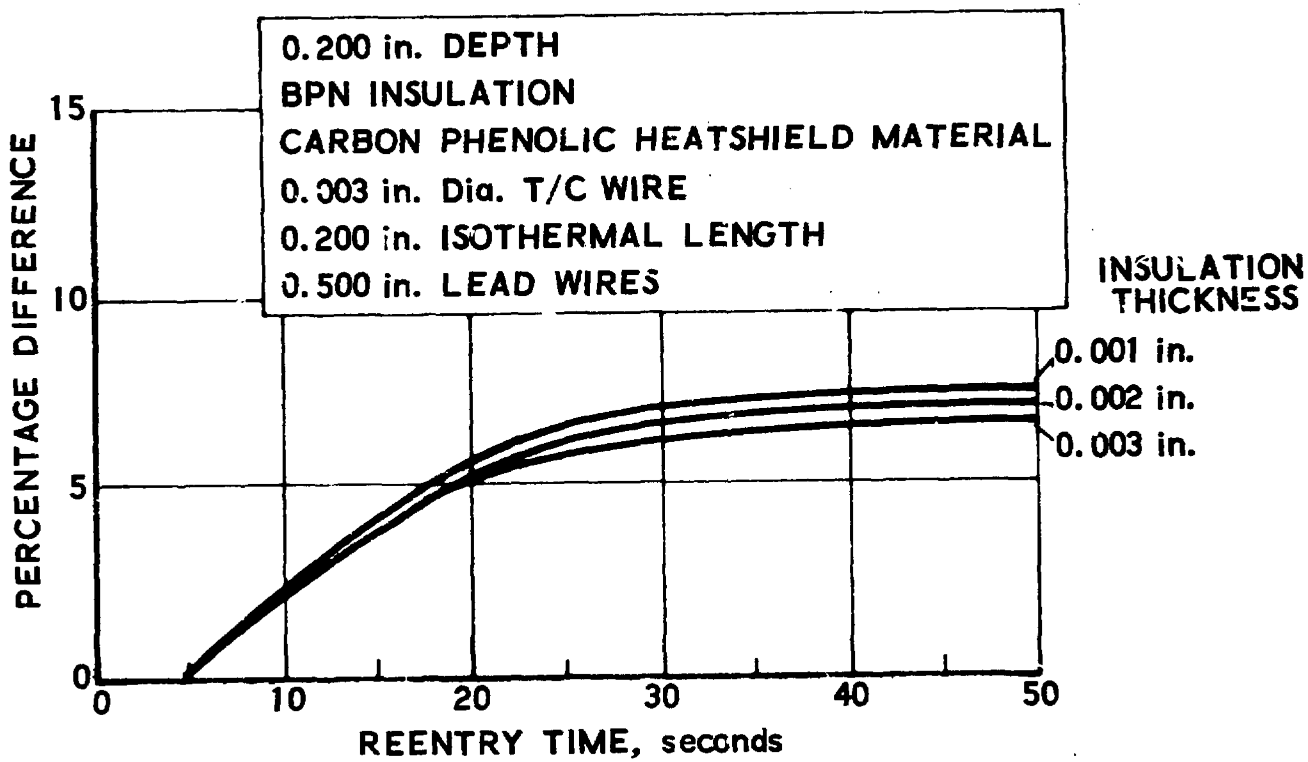


Fig. 9 Insulation Thickness Effects

Isothermal Length Effects

Since the isothermal length of the thermocouple governs the width of the thermocouple plug, it is important to determine the minimum isothermal length for a heatshield in order to keep the discontinuity of the plug in the heatshield to a minimum. As shown in Figs. 10, 11, and 12, the accuracy effects of isothermal lengths of 0.100, 0.150, and 0.200 in., respectively, were studied for the basic carbon phenolic plug studied in the previous sections with 0.001-in. BPN insulation thickness for the 0.001, 0.003, and 0.005-in. diameter wires. The results plotted in Fig. 10 show an increase in maximum percentage difference from 5.1 to 5.9 percent as the isothermal length decreases from 0.200 to 0.100 in. The percentage difference increases with wire size, per Figs. 11 and 12, where the maximum percentage increases from 7.5 to 11.3 and 11.8 to 18.2 percent as the isothermal length decreases from 0.200 to 0.100 in. for wire diameters of 0.003 and 0.005 in., respectively.

As the isothermal length decreases to zero, it should be noted that the isothermal thermocouple becomes the post type thermocouple with its 25 to 50 percent difference [2, 9]. The conclusion that the percentage difference increases with an increase in wire size and a decrease in isothermal length is therefore expected. However, Figs. 10 through 12 do show that the minimum, recommended isothermal lengths for 0.005 in. and 0.003-in. diameter wires are 0.200 and 0.150 in., respectively. Even then, the 0.100-in. isothermal length for the 0.003-in. diameter wire yields virtually the same accuracy as the 0.200-in. isothermal length of a 0.005-in. diameter wire.

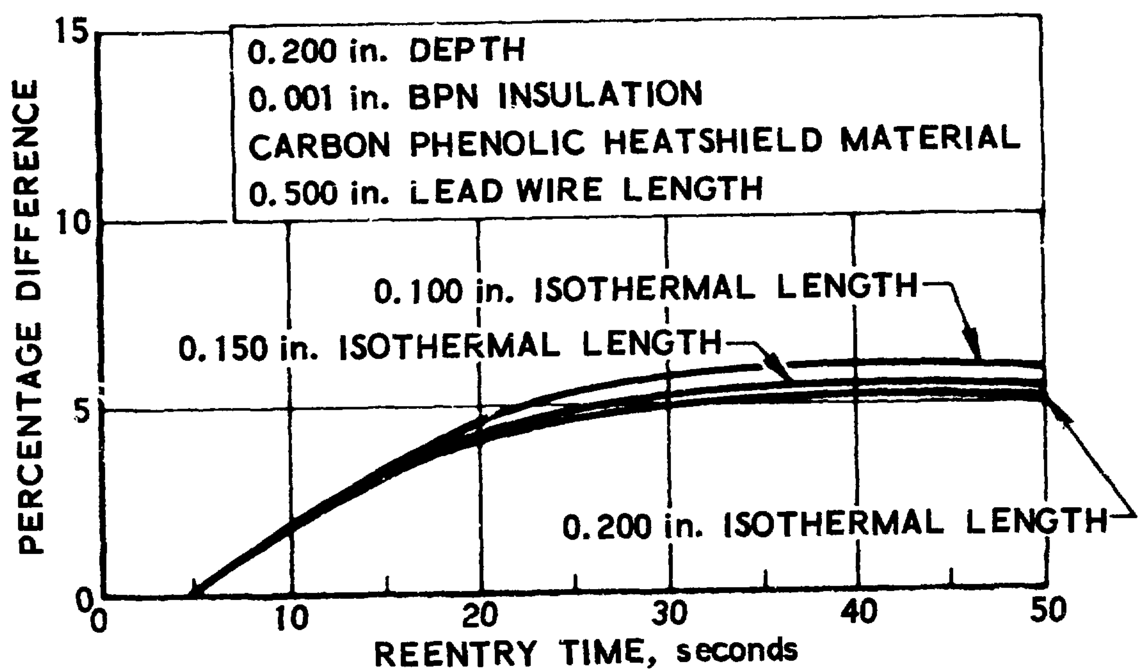


Fig. 10 Isothermal Length Effects, 0.001-in. Diameter Wire

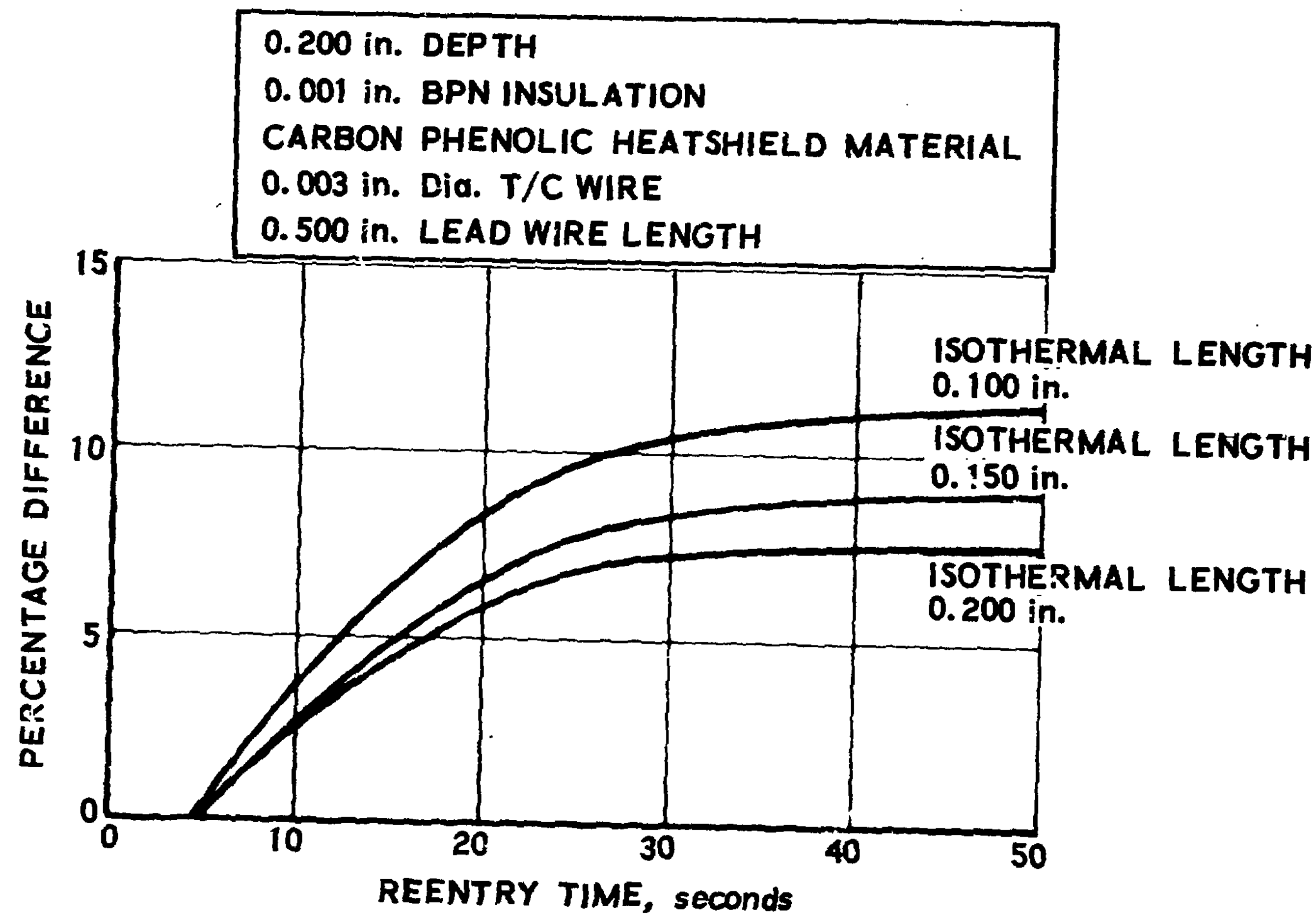


Fig. 11 Isothermal Length Effects, 0.003-in. Diameter Wire

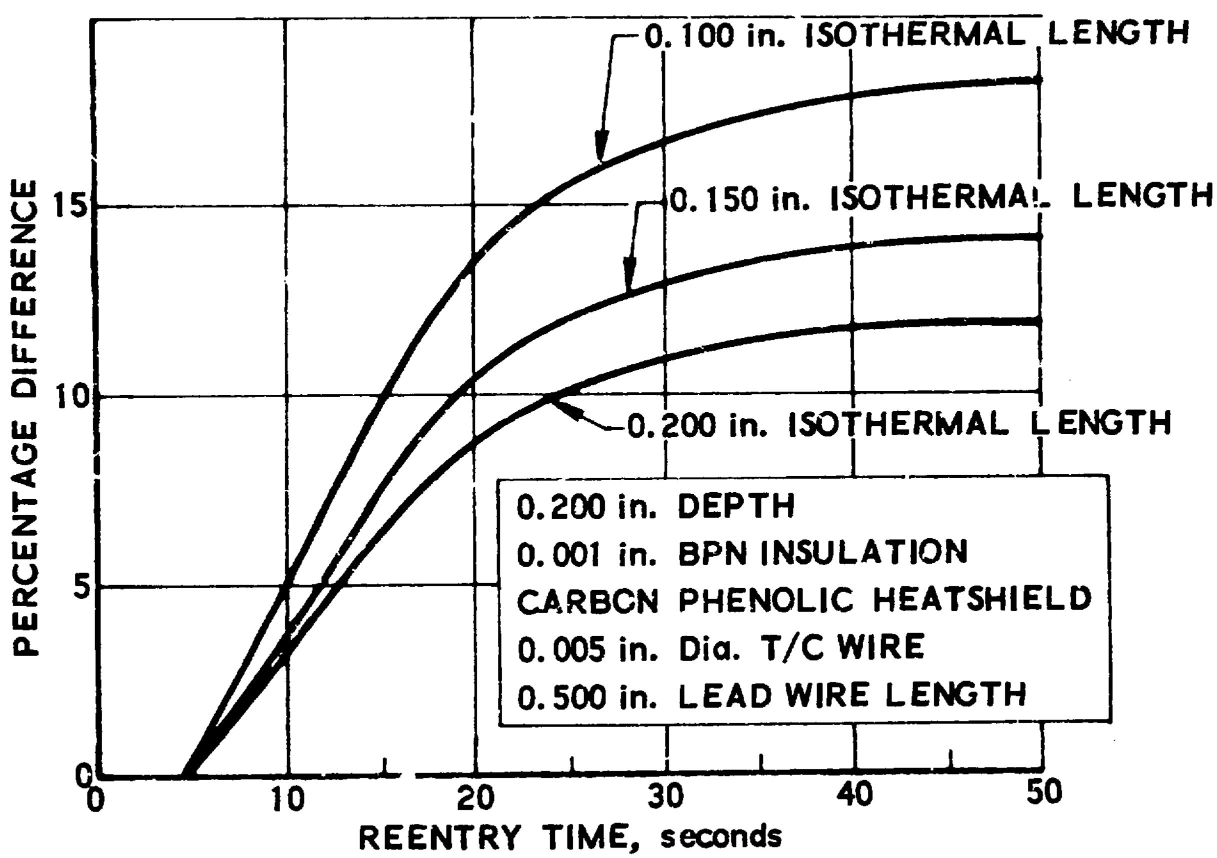


Fig. 12 Isothermal Length Effects, 0.005-in. Diameter Wire

This means that a 0.250-in. isothermal length of a 0.005-in. diameter wire is really required to deliver the same accuracy of a 0.003-in. diameter wire with a 0.150-in. diameter isothermal length.

Lead Wire Length Effects

The lead wire length of a thermocouple, as defined in Fig. 1, can vary from 0.100 to 1.0 in. The average lead wire length is about 0.400 in.; therefore, the 0.100, 0.300, and 0.500-in. lengths investigated in this study are representative of the lengths used in contemporary ballistic reentry vehicle multiwire isothermal thermocouple plugs. The importance of the lead wire length and diameter is related to the heat leakage from the thermocouple junction via the isothermal length into the lead wires and extension cable. As the lead wire length increases, its thermal resistance increases as well as its thermal capacity. Also, as the lead wire diameter increases, its thermal resistance decreases, and its thermal capacity increases. Therefore, an increase in lead wire diameter should yield a lower thermocouple reading, whereas an increase in lead wire length may or may not affect the thermocouple measurement, depending, of course, on the material properties of the thermocouple wires. For example, as the thermal conductivity of a wire increases, its ability to conduct heat increases, and more heat will be conducted away from the thermocouple junction and yield a lower temperature reading. Conversely, as the thermal conductivity of a wire decreases, its ability to conduct heat decreases, and less heat will be conducted away from the thermocouple junction and yield a higher thermocouple reading than with the higher thermal conductivity wire. Note that the lead wires are connected to the extension cable wires (see Fig. 1), which transmit the thermocouple millivolt output to the reentry vehicle telemetry system, and that these transmission wires are, in fact, infinite sinks. However, as the following results show, the thermal resistance of the

0.001 and 0.003-in. lead wires will permit little heat to be transferred into the transmission wires. The results of the lead wire length effects study are similar to those for the isothermal wire length effects. In Fig. 13, the maximum percentage difference varies from 6.2 to 5.8 percent as the lead wire length decreases from 0.500 to 0.100 in. for the 0.001-in. diameter wire which is considered to be negligible. The maximum percentage difference for the 0.003 and 0.005-in. diameter wires varies from 9.6 to 6.2 and 14.5 to 8.2 per Figs. 14 and 15, respectively, as the lead wire length decreased from 0.500 to 0.100 in.

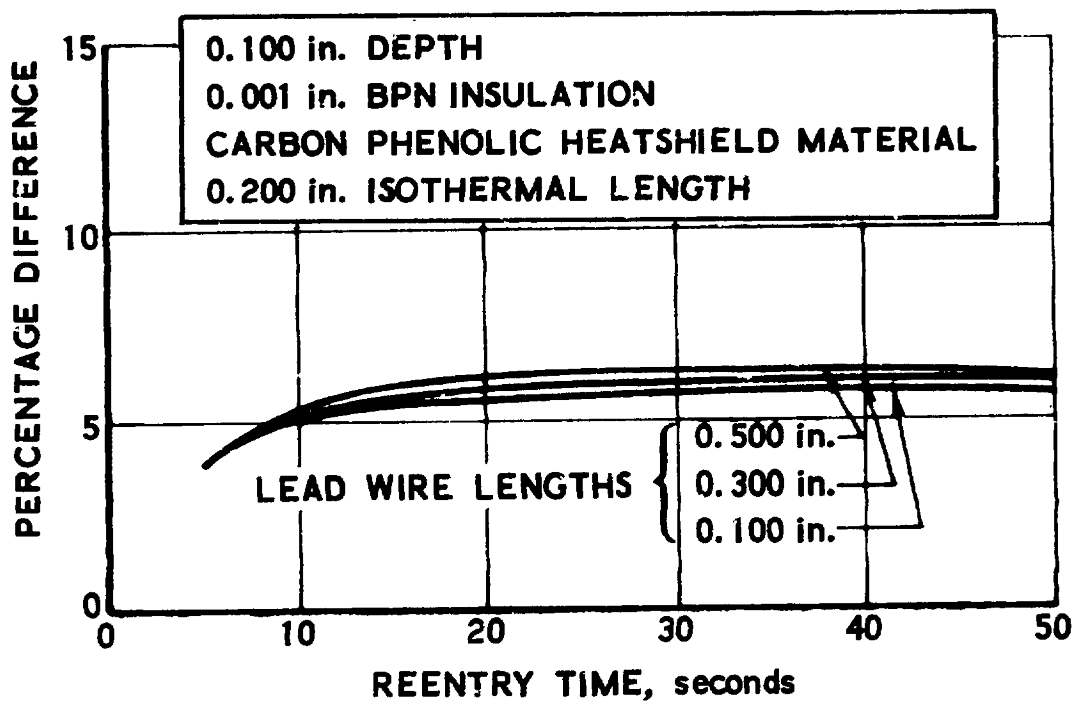


Fig. 13 Lead Wire Length Effects, 0.001-in. Diameter Wire

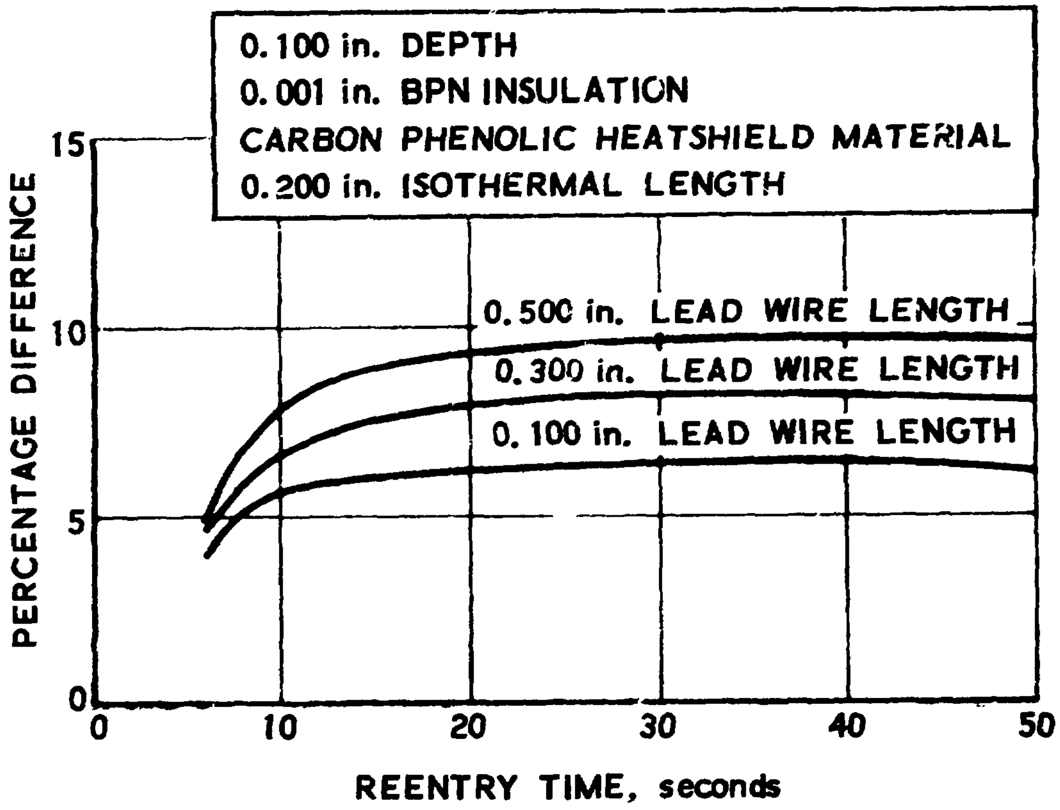


Fig. 14 Lead Wire Length Effects, 0.003-in. Diameter Wire

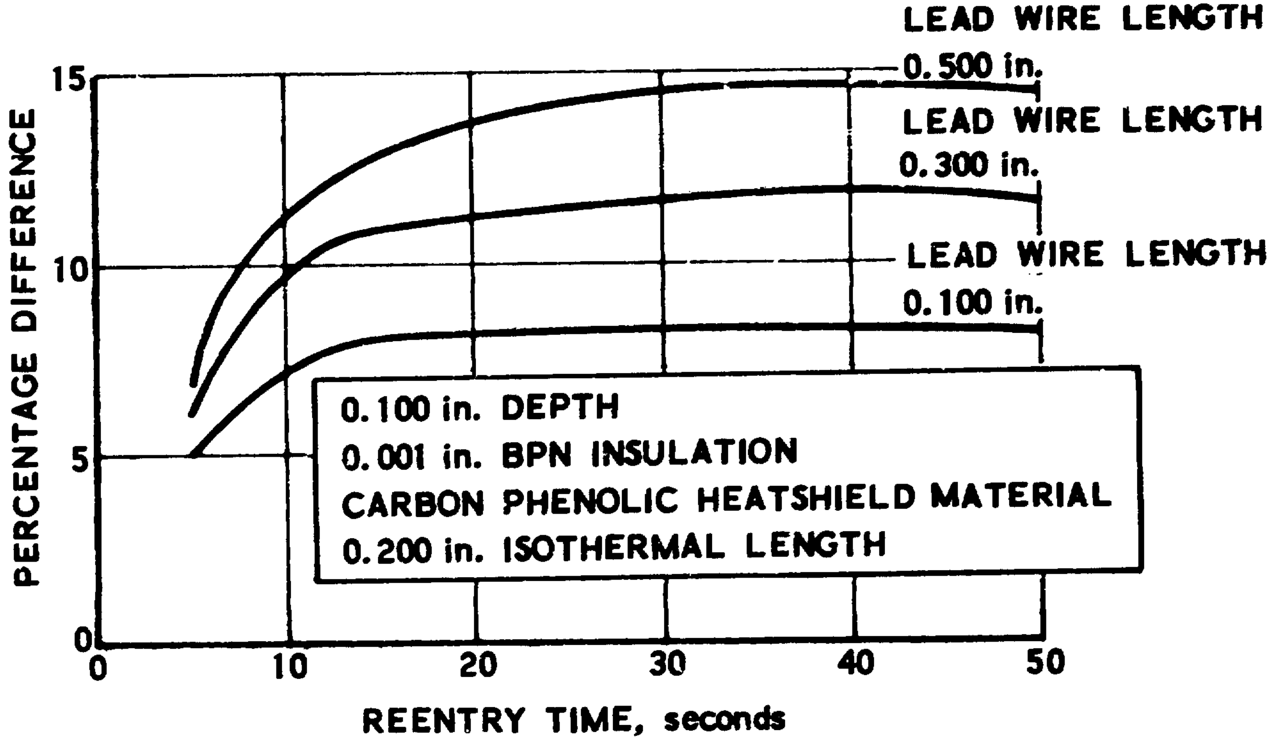


Fig. 15 Lead Wire Length Effects. 0.005-in. Diameter Wire

Askew Installation Effects

One isothermal thermocouple installation specification frequently encountered is the dimension tolerance for the location of the thermocouple junction and isothermal length at a specified depth from the surface of the heatshield. This specification usually reads in the format that the thermocouples shall be located to within ±0.002 in. of the designated depths. This depth location problem is also related to the askewness of the isothermal length. However, since the thermoconductivity of the W26Re/W5Re thermocouple wire (0.0165 to 0.0200 Btu/sec-ft-°F) is so much higher than that for the carbon phenolic (0.00012 Btu/sec-ft-°F), and the tape wrapped quartz phenolic (0.000065 Btu/sec-ft-°F) heatshield materials, the temperature along the length of the isotherm from the junction to the lead wire is essentially the same. Hence, the error due to the mislocation of the junction in the heatshield is simply the error associated with obtaining the temperature at a wrong depth in the heatshield. For example, if one desires the temperature history of a heatshield at a point 0.050 in. below the heatshield surface but instead installs the thermocouple at 0.075 in., the data correlation will be in error if one tries to match a 0.050-in. temperature history measurement. Fortunately, it is standard practice to X-ray the isothermal thermocouple plugs [2] in order to determine the location of the junctions to within ±0.001 in. of the actual depth. Therefore, the analyst is able to correct the input to his computer programs accordingly to match a 0.050-in. temperature history prediction to the measured 0.050-in. temperature history. This reduces the importance of the askew installation study effects to that of determining reasonable tolerances in specifying the desired locations. As shown in Fig. 16, the maximum percentage difference for the thermocouple junctions located from 0.001 to 0.005 in. nearer to the surface than specified, is between 3.7 and 4.3 percent, where 3.6 percent of the difference is associated with the presence of the 0.003-in. diameter wire with its 0.001 in. of BPN insulation in the tape wrapped quartz phenolic heatshield material. However, the thermocouple junction mislocation of 0.010 in. increases the total maximum percentage difference to 6.2 percent (almost 2 percent over the 0.005-in. case). These results are also consistent with those obtained in [7]. Therefore, it is concluded that isothermal length askewness and the mislocation of the thermocouple in-depth location tolerances of ±0.005 in. would be acceptable at the 0.100-in. depth studied in this case and at deeper locations in the heatshield.

Note that this specific study was made for a tape wrapped quartz phenolic heatshield material plug, whereas the previous discussions were based on plugs fabricated from the carbon phenolic heatshield materials. Since the thermal conductivity of the tape wrapped quartz phenolic is higher than that for carbon phenolic, the ±0.005-in. tolerances determined for the tape wrapped quartz phenolic will also apply to the carbon phenolic.

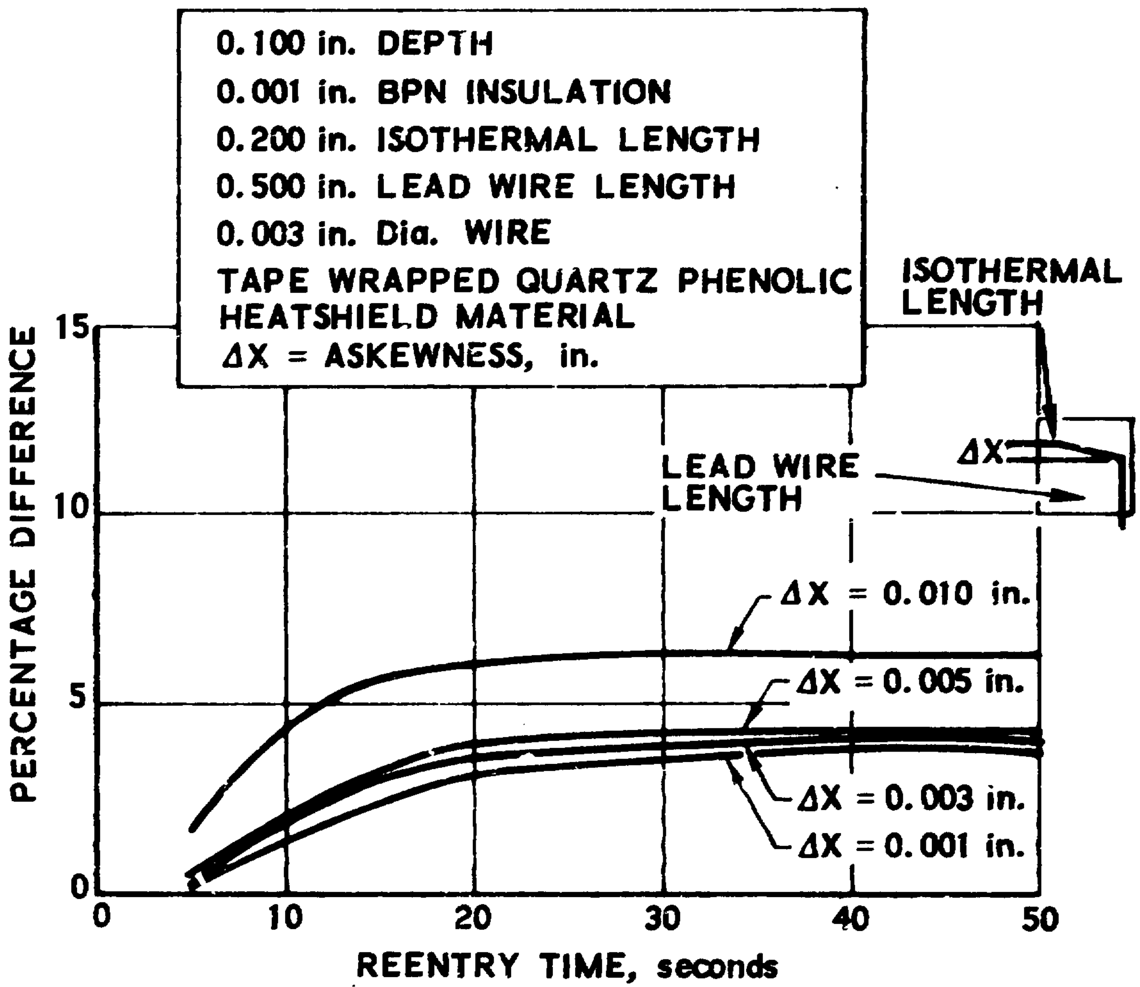


Fig. 16 Askew Installation Effects

Trajectory Effects on Thermocouple Performance

The study to determine the effects of different reentry trajectories on isothermal thermocouple performance was based on a 0.005-in. diameter thermocouple wire covered with 0.001 in. of BPN electrical insulation and installed in the tape wrapped quartz phenolic heatshield material 0.200 in. below the heatshield with 0.500-in. lead wires. This specific configuration was flown on a number of ballistic reentry vehicles during the late 1960s. The trajectories ranged in reentry angles from -6 to -40 deg with initial reentry velocities on the order of 22,500 fps for the 6, 30, and 40-deg trajectories and 15,500 fps for the 24 deg trajectory. The 6, 30, and 40 deg at 23,500 fps velocity trajectories were the primary trajectories under consideration, but the 24 deg, 15,500 fps trajectory was also included, because a lot of data had been obtained on a reentry vehicle flying this trajectory [2]. All of the trajectories considered started at 300,000 ft and terminated at impact.

The Fig. 17 results, in terms of percentage difference versus time, show that the percentage difference increases with penetration into the earth's atmosphere and with the steepness of the reentry angle. At the beginning of reentry, the percentage difference is zero, or near zero, as the thermocouple system measures and registers the initial vehicle soak temperature in the heatshield. As the vehicle reenters, the heat input to the heatshield increases, the heatshield temperature increases, and the thermocouple system measures and registers the temperature history of the heatshield. The steeper the reentry angle for a given reentry velocity, the higher the peak heating rate. Also, the higher the heating rate, the faster the temperature

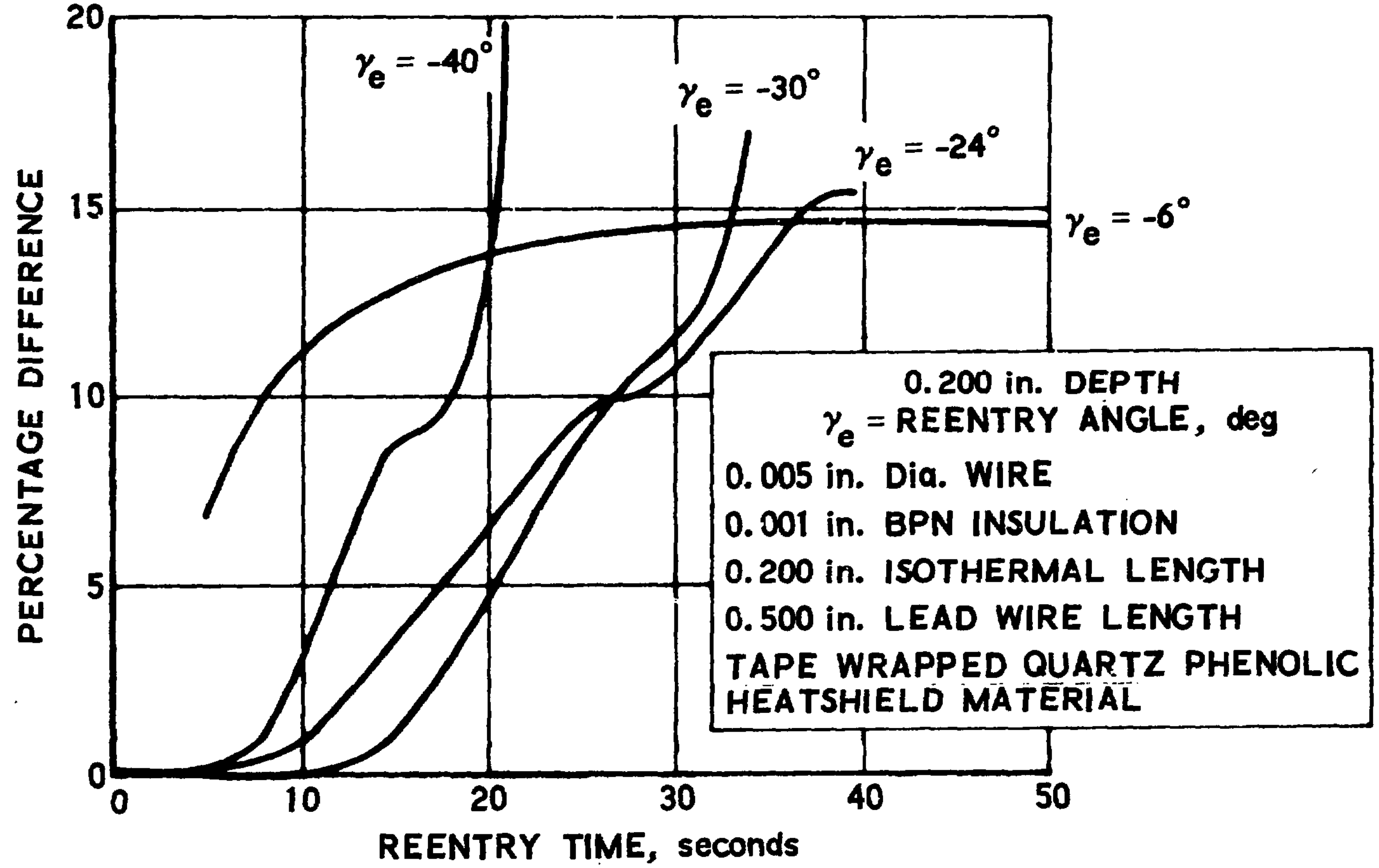


Fig. 17 Trajectory Effects on Thermocouple Performance

response of the heatshield and the higher the percentage difference between the actual and measured heatshield temperatures due to the time lag of the thermocouple system. The maximum percentage difference (at impact) versus reentry angle is plotted on Fig. 18.

Figures 17 and 18 also are indicative of the problems encountered in the simulation of the isothermal thermocouple plug, because [2] shows that the predicted and measured temperature histories correlated to within a range of 0 to 5 percent of the measured temperature histories for most of the thermocouples located between 0.100 and 0.200 in. below the heatshield surface for the 24 deg, 15,000 fps trajectory. This is especially perplexing inasmuch as some thermodynamicists in the ballistic reentry vehicle industry doubt if we can calculate the aerodynamic heating to within 10 percent in some altitude ranges and 20 percent in others.

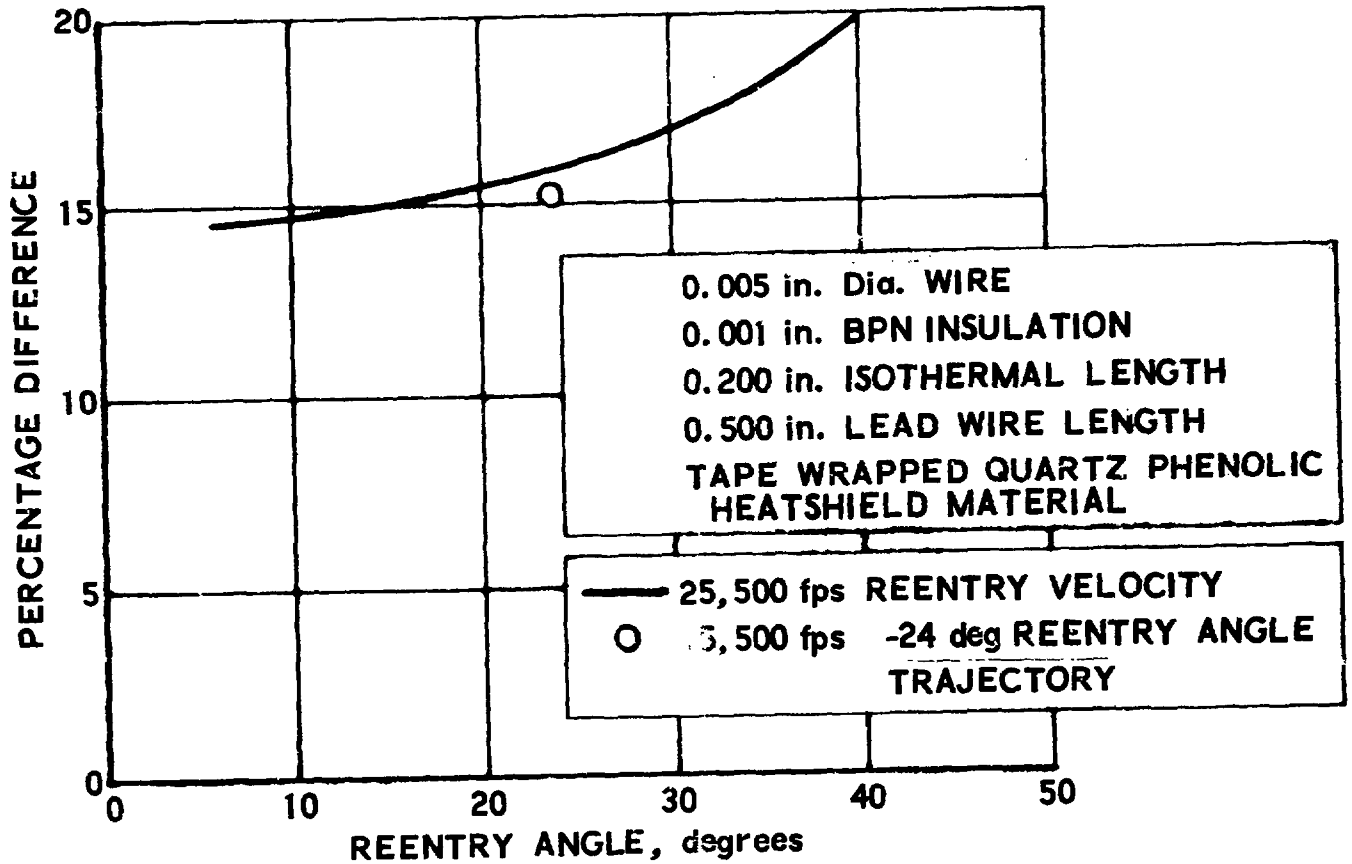


Fig. 18 Trajectory Effects on Thermocouple Performance at Impact

Heatshield Material Effects

There are a number of ablative materials used for the heat protection systems on ballistic reentry vehicles. Two representative materials are tape wrapped quartz phenolic and carbon phenolic, where the tape wrapped quartz phenolic represents the glassy class of ablators, and the carbon phenolic represents the carbonaceous class. The primary difference between the two classes is their operating temperatures. According to the tests reported in [10], the phenolic in both materials starts to pyrolyze near 400°F. As the temperature rises to several thousands of degrees fahrenheit, the phenolic in the outer layers of the heatshield has been boiled out leaving a glassy char (carbonized phenolic deposited on the glass fibers) in the case of the glassy ablator, and a carbonaceous char (carbonized phenolic deposited on the carbon fibers) in the case of the carbonaceous material. At 4300°F, the glassy material is assumed to melt and the heatshield surface recedes as the melted glass is removed by the shearing forces in the boundary layer. The carbon char is assumed to sublimate at 6600°F unless it is removed by boundary layer shear forces at lower temperatures.

Both materials have somewhat similar specific heats in the lower temperature ranges (0.35 Btu/lb-°F at 400°F for carbon phenolic and 0.36 Btu/lb-°F at 1000°F for tape wrapped quartz phenolic), while the virgin plastic density is 90 lb/cu ft for the carbon phenolic and 109 lb/cu ft for the tape wrapped quartz phenolic. This gives the tape wrapped quartz phenolic more thermal capacitance than the carbon phenolic on a unit weight or a unit thickness basis (see Table A-5 for temperature dependent properties of carbon phenolic and tape wrapped quartz phenolic). The thermal conductivities for the carbon phenolic and the tape wrapped quartz phenolic in the lower temperature range (1000°F) and 0.000065 and 0.00012 Btu/sec-°F-ft, respectively, so that the thermal resistance of the carbon phenolic is less than that of the tape wrapped quartz phenolic. When the differences in specific heat, density, and thermal conductivity are considered (in short, the thermal diffusities), it is seen that a unit thickness of the carbon phenolic will heat up faster than a unit thickness of the tape wrapped quartz phenolic. In Fig. 19, the percentage differences between the undisturbed heatshield case and the heatshield with a 0.003-in. thick diameter wire and a 0.001-in. BPN insulation thickness are plotted for both the carbon phenolic and the tape wrapped quartz phenolic materials at 0.020, 0.100, and 0.200-in. depths and thicknesses. In all cases, the carbon phenolic plugs yield higher percentage differences, but at the 0.100 and 0.200-in. depths, the variances in percentage differences are negligible for most temperatures. Most of the percentage difference at the 0.020-in. depth is attributable to the simulation problems discussed in the Analysis Model Section. Also, in a two-dimensional 0.020-in. finite slab, a pair of 0.003 to 0.005-in. diameter wires represent a considerable thermal sink percentage of the material present (15 to 25 percent), whereas in a two-dimensional 0.100-in. finite slab they represent only a 3 to 5 percent thermal sink effect.

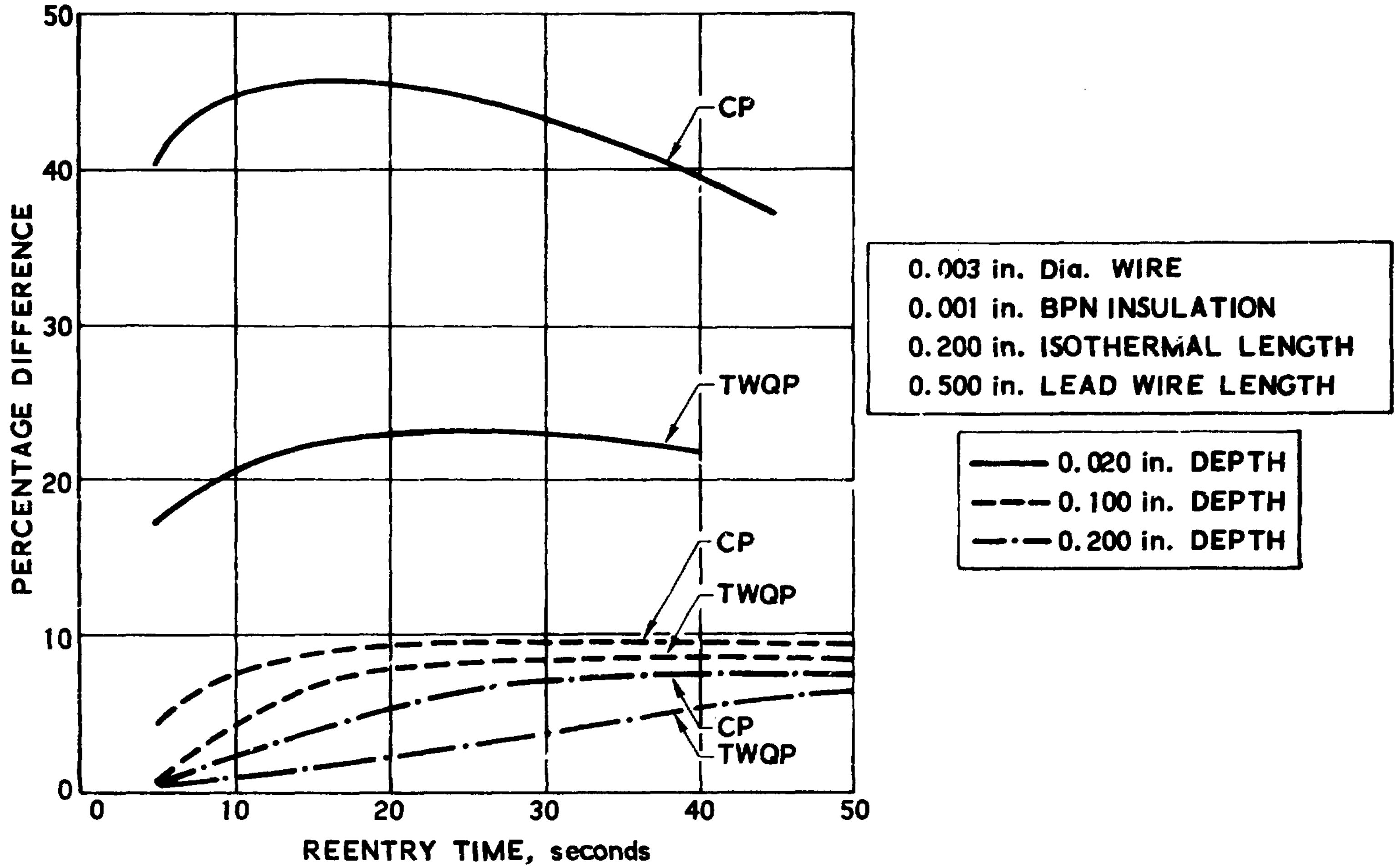


Fig. 19 Heatshield Material Effects

Potting Compound Effects

When the insulated thermocouple wires are installed in the plugs, a filler material must be used to fill in the voids around the insulated wire in the channel it is installed in per Fig. 6. This potting compound is usually made from the basic phenolic from which the heatshield is fabricated plus powdered heatshield material. In the thermal capacitances and resistances of the simulation, the cases where the potting compound is considered 100-percent carbon phenolic and 100-percent phenolic were considered. As shown in Figs. 20 and 21, the percentage differences between the two cases is less than 1 percent for 0.005-in. diameter wires and 2 percent for the 0.003-in. diameter wires. Since these differences were so small, no further cases were considered. If further cases had been required, the thermodynamic properties of a phenolic/carbon phenolic potting compound would have been determined per the [11] procedures.

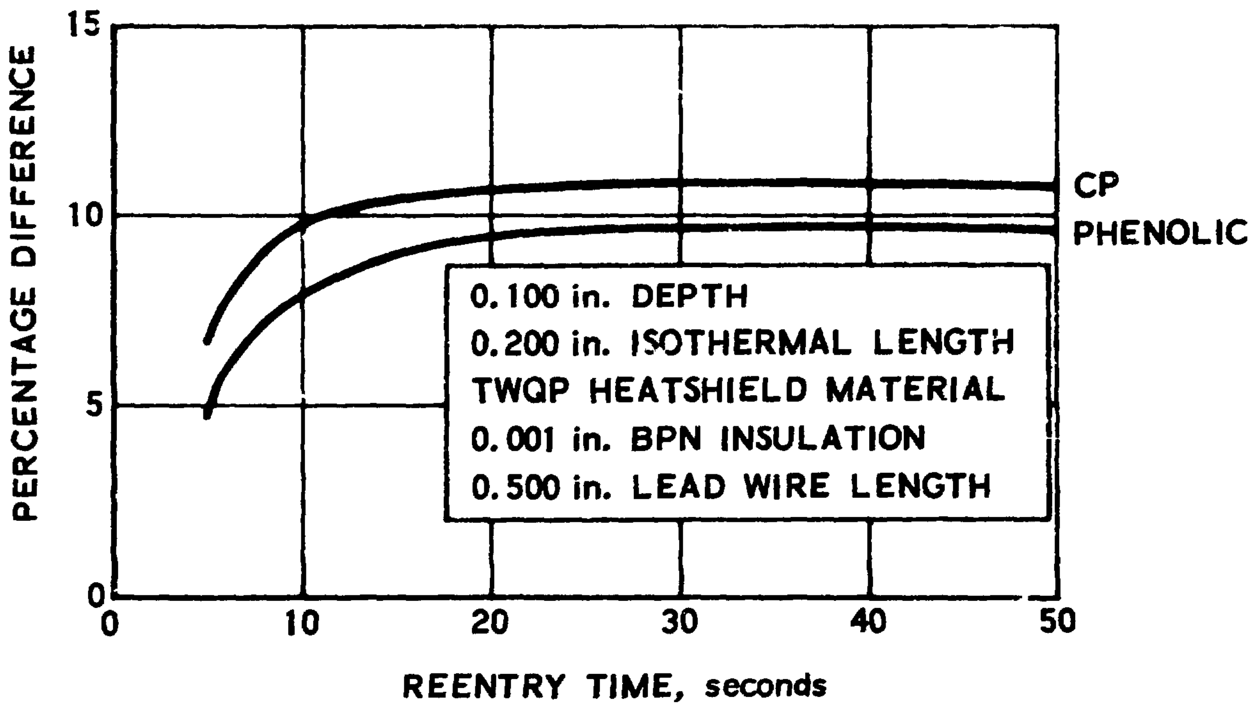


Fig. 20 Potting Compound Effects, 0.003-in. Diameter Wire

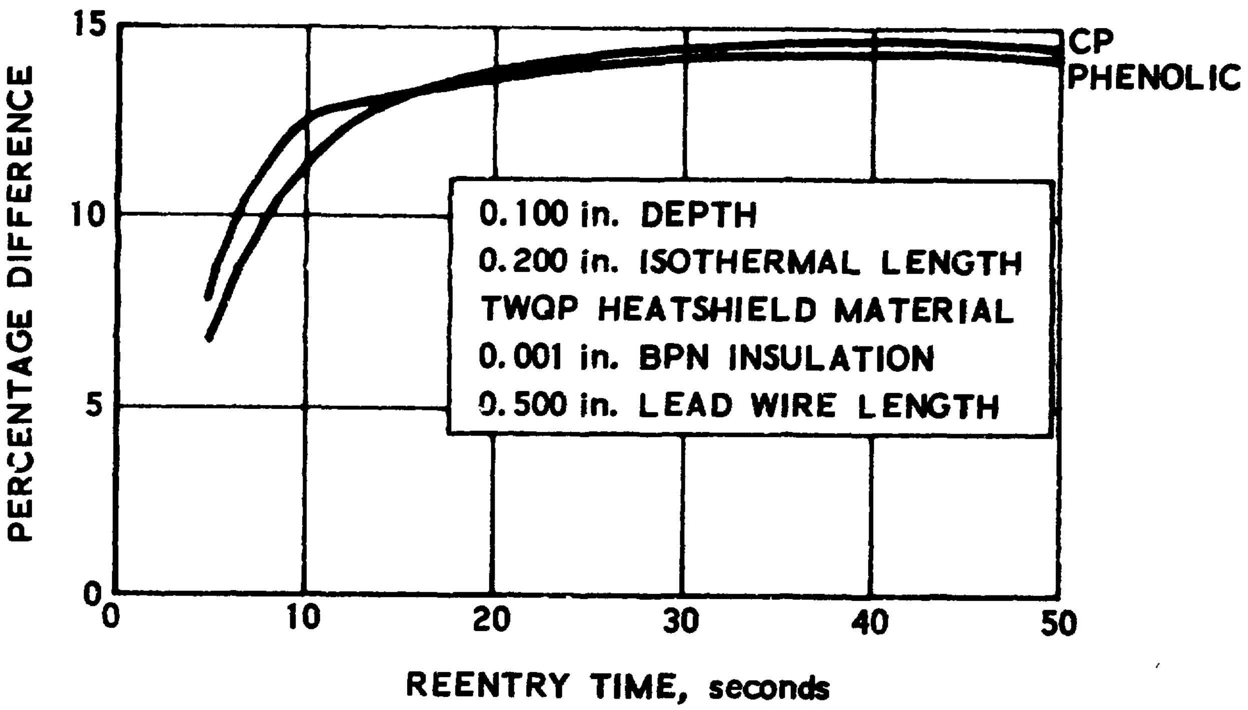


Fig. 21 Potting Compound Effects, 0.005-in. Diameter Wire

Thermocouple Interference Effects

There may be up to four thermocouples in a multiwire isothermal thermocouple plug in either the Fig. 4 or 5 configuration, and the question arises as to what effect one wire has on another. If one wire is located above the other as shown in Fig. 22A, with their isothermal lengths parallel or nearly parallel to each other, then the case of maximum interference is obtained because the heat transferred to the deeper thermocouple wire must first pass through the wire assembly nearer the surface. In the ideal case as shown in Fig. 22B, the wires would be installed without any overlapping of the wires at all. For this study, the case of maximum interference will be examined in a carbon phenolic thermocouple plug 0.410-in. thick with up to three thermocouples installed per Fig. 22A. The simulation for the 0.410-in. plug was simplified to where only the thermal capacitive effects of the thermocouple wires and electrical insulation were considered.

The results of this study in the form of percentage differences were plotted on Figs. 23 through 25, for 0.003-in. diameter wire (0.200-in. isothermal length) insulated with 0.001-in. BPN for the thermocouple interference effects at 0.020, 0.100, and 0.200 in., respectively. This study considered all combinations for three wires in the plug. These results essentially show that:

1) The percentage difference decreases as thermocouple depths increase for single thermocouple installations as discussed in a previous section. Thus, there is more percentage difference error associated with the 0.020-in. depth installation than with the 0.100 or 0.200-in. depth installations.

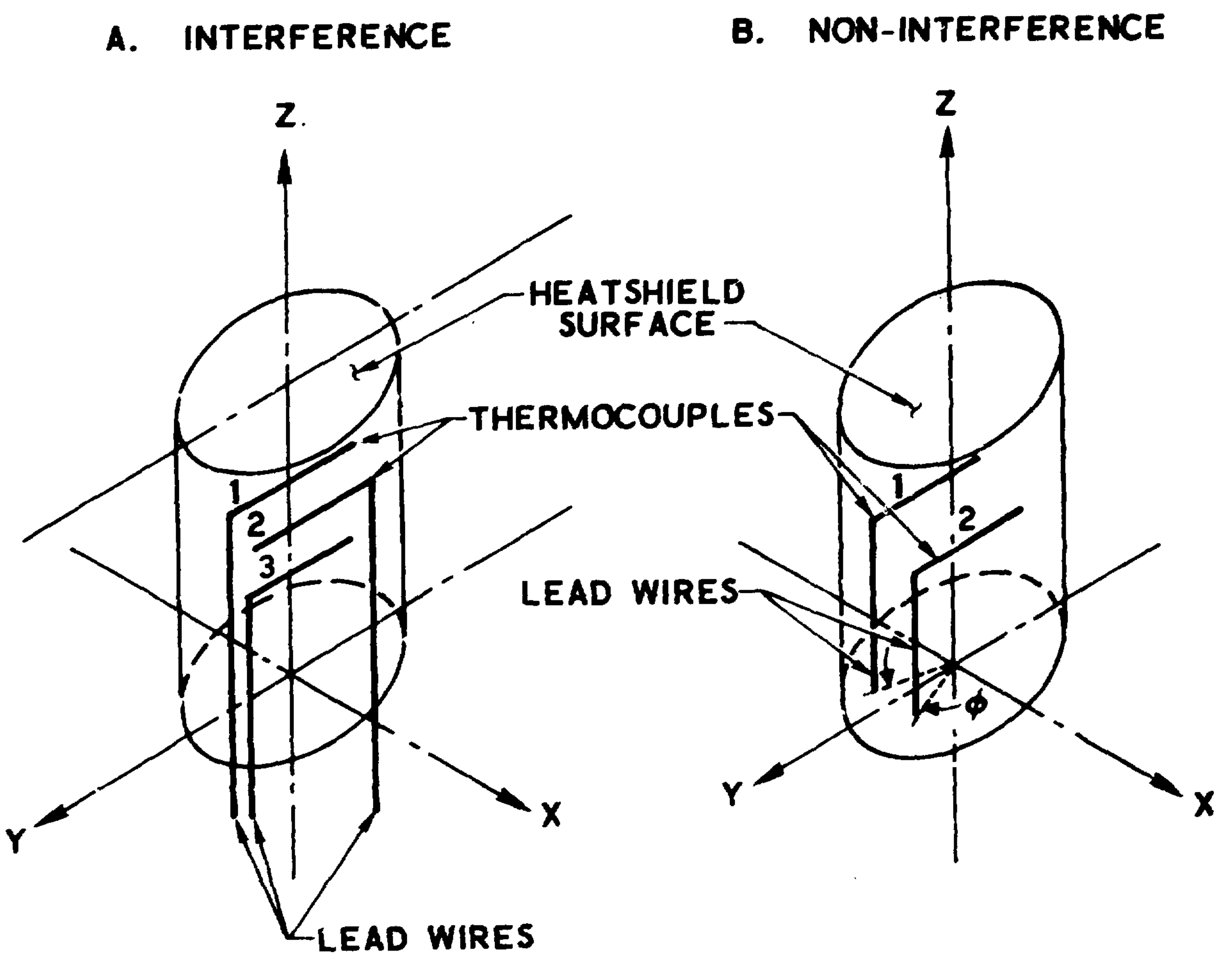


Fig. 22 Multiwire Isothermal Thermocouple Plug Installation

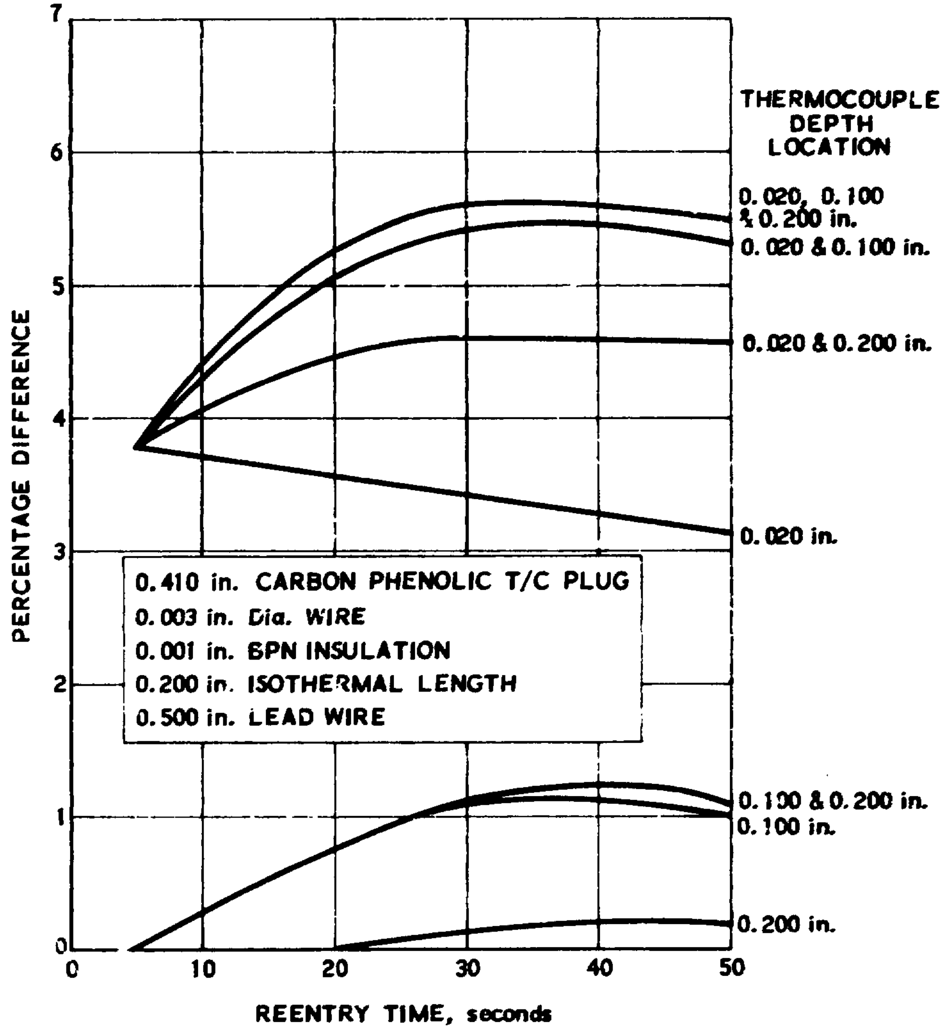


Fig. 23 Thermocouple Interference Effects, 0.020-in. Depth

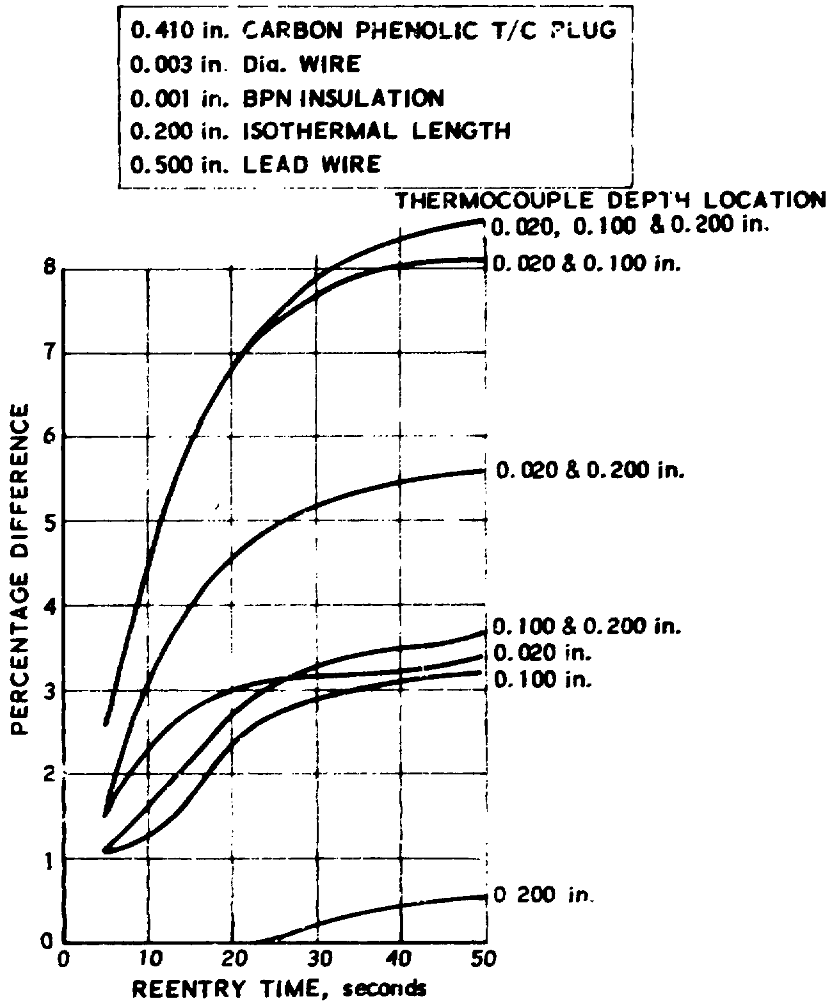


Fig. 24 Thermocouple Interference Effects, 0.100-in. Depth

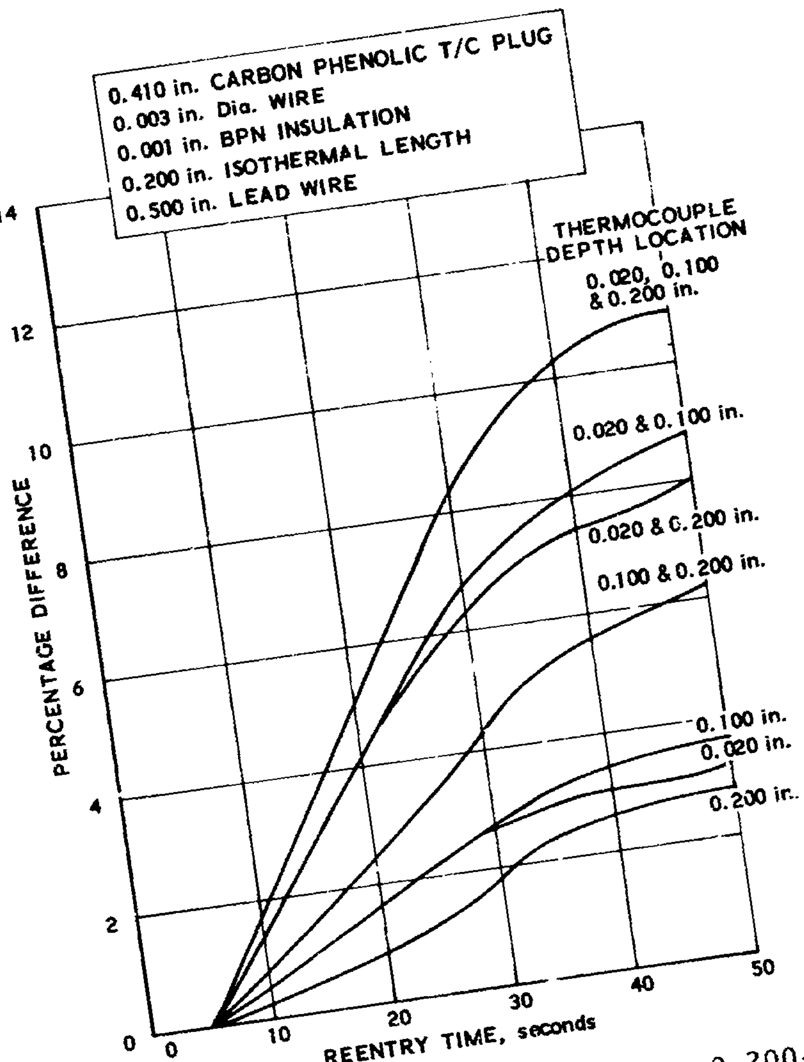


Fig. 25 Thermocouple Interference Effects, 0.200-in. Depth

2) The percentage difference increases with the number of thermocouples installed in a plug.

3) The total maximum percentage difference increased from about 5.6 to 10.9 percent as the depths increased from 0.020 to 0.200 in.

4) With the exception of the last 15 seconds for the 0.020-in. depth case, all of the calculated temperature histories (1200°F) were within the acceptable accuracy range of the simulation.

Similar results were plotted in Figs. 26 through 28 for the 0.005-in. diameter wire. Per the previous wire size effects discussion, all of the 0.005-in. diameter wire results were higher than those for the 0.003-in. diameter wire size. Only the 0.003 and 0.005-in. wire sizes were considered at this stage of the overall investigation, because they represent configurations which have or will be flown.

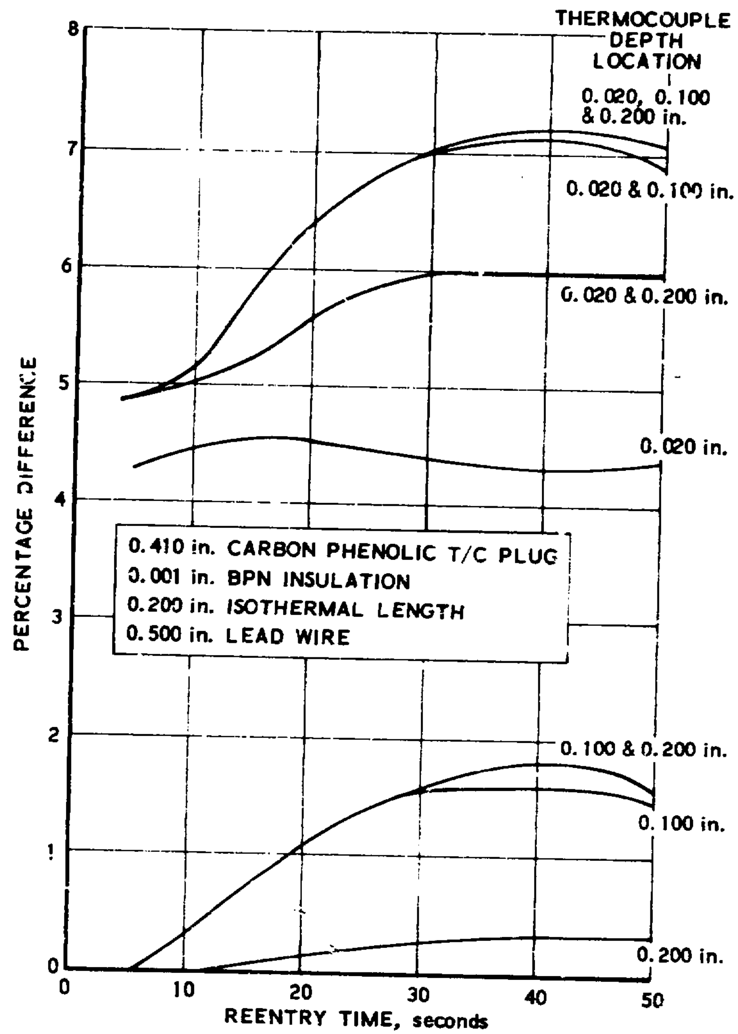


Fig. 26 Thermocouple Interference Effects, 0.020-in. Depth, 0.005-in. Diameter Wire

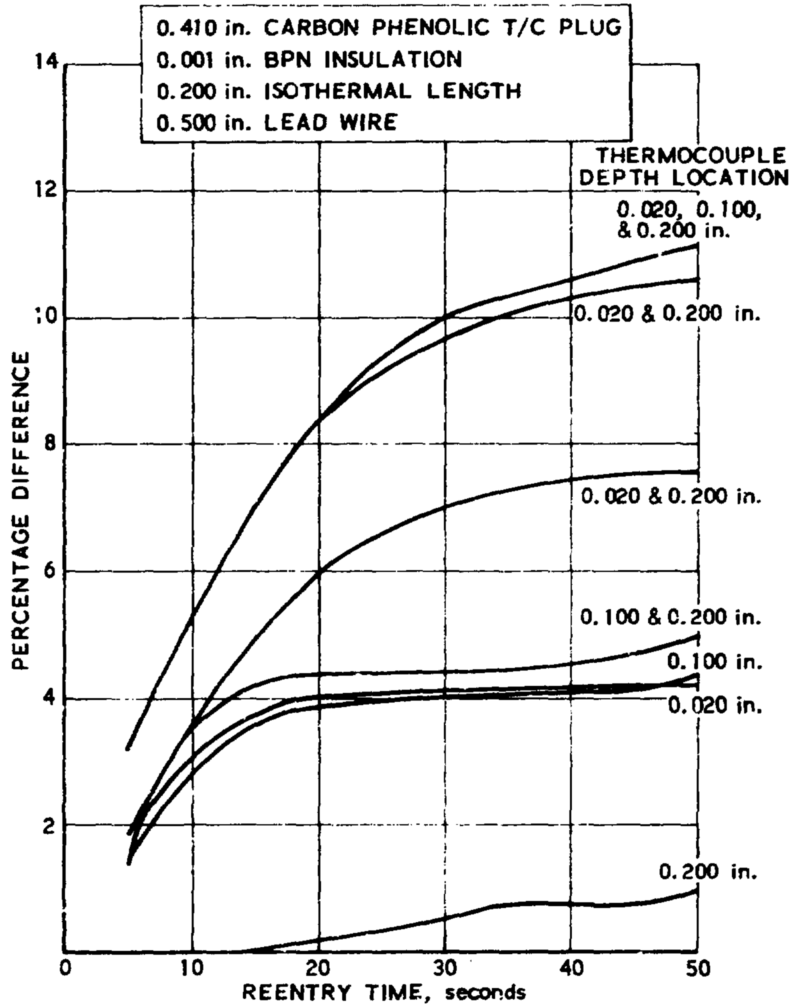


Fig. 27 Thermocouple Interference Effects, 0.100-in. Depth, 0.005-in. Diameter Wire

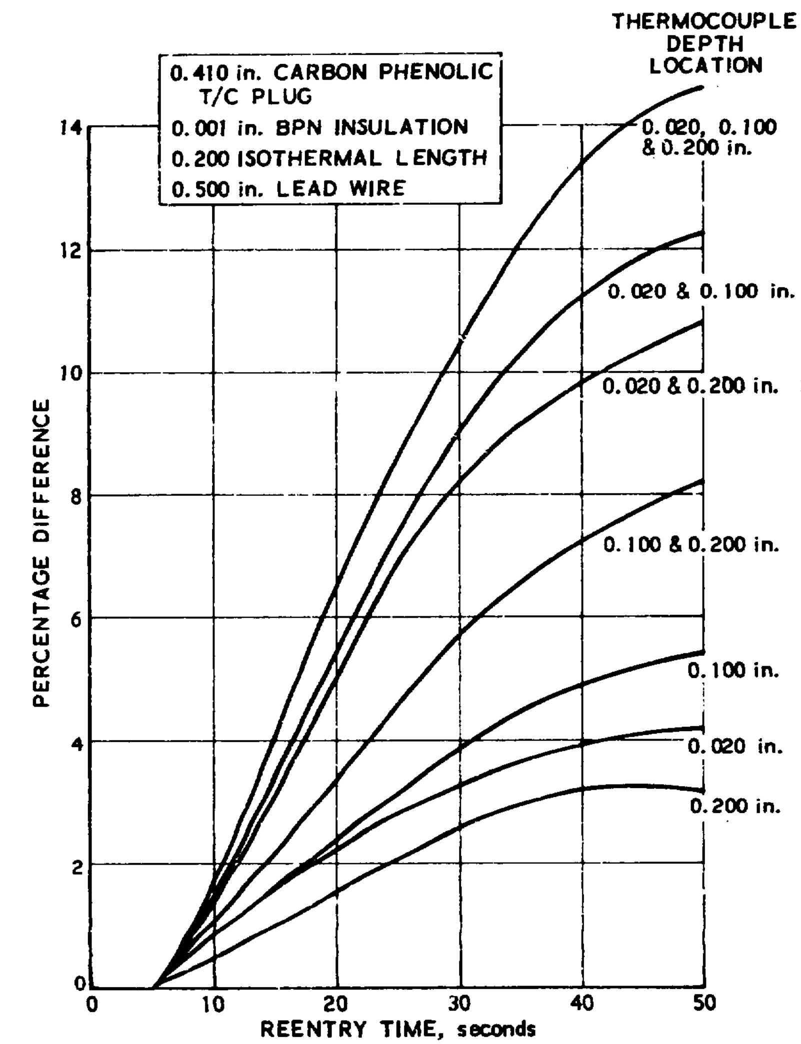


Fig. 28 Thermocouple Interference Effects, 0.200-in. Depth, 0.005-in. Diameter Wire

Summary

The results of this analytical study of the isothermal thermocouple commonly used on ballistic reentry vehicles are summarized as follows.

1) The thermocouple's accuracy increases with decreasing wire diameter, decreasing lead wire length, increasing isothermal length, and increasing installation depth of the thermocouple relative to the heatshield surface.

2) The effects on thermocouple accuracy from the variations of electrical insulation thickness is negligible for the thicknesses presently encountered in design.

3) The heatshield material effect on thermocouple accuracy is a strong function of the heatshield material insulative qualities with thermocouple accuracy increasing with decreasing density and thermal conductivity of the heatshield material.

4) The more severe the instantaneous heat flux and the peak heat flux due to the trajectory, the less accurate the thermocouple measurement.

5) The askewness in the installation of the thermocouple isotherm is not as significant as the accuracy in obtaining the designed depth in the thermocouple junction installation.

6) The amount of ground, or powdered, heatshield material in the phenolic of the potting compound did not have much of an effect on the thermocouple accuracy.

7) The interference effects from multiwire thermocouple installations were additive for wires whose isothermal lengths were aligned with and over each other and were negligible for wires whose isothermal lengths are not aligned with and over each other.

Recommendations

The following recommendations are based on the preceding summary of results.

1) Decrease the established reentry vehicle isothermal thermocouple wire diameter from 0.005 to 0.003 in. It may not be feasible at this time to use the 0.001-in. diameter wire considering the ultimate increase in expense due to the handling problems for the 0.001-in. wire.

2) For maximum accuracy, use minimum isothermal lengths of 0.150 and 0.200 in. for 0.003 and 0.005-in. diameter wires, respectively.

3) Locate the thermocouple wires to within ±0.005 in. of the desired depth for depths of 0.100 in. or greater.

4) Minimize the interference effects from multiwire thermocouple installations as much as possible.

APPENDIX A

As discussed briefly in the Analysis Model Section of this report, the isothermal thermocouple plug assembly, both in the single and multiwire configurations, was simulated with the [3] computer program, which is known in the aerospace industry as a "thermal analyzer type" computer program. When using this computer program, the analyst constructs and analyzes a mathematical model of any arbitrary one-, two-, or three-dimensional lumped-parameter representation of a physical system governed by a set of diffusion equations (i.e., the Fourier equation with an additional source term). To utilize this program, the analyst must construct a thermal analog network representation of the physical system, uniquely number all of the elements, and input the information in the required format. In other words, this computer program simulates a physical system as a finite number of small elemental volumes with their associated thermal capacitances and connected in one-, two-, or three-dimensional arrays via thermal resistances. Figure A-1 represents the simulation for the multiwire isothermal thermocouple plug which is 0.410 in. long with a 0.200-in. isothermal length and a 0.500-in. lead wire length.

Note on Fig. A-1 the aerodynamic heat fluxes, q_1 through q_4, inclusive. These provide the driving thermal current into the network. They are calculated by the Ascent Heating Subroutine in [3]. The required inputs to this subroutine are the vehicle geometry and

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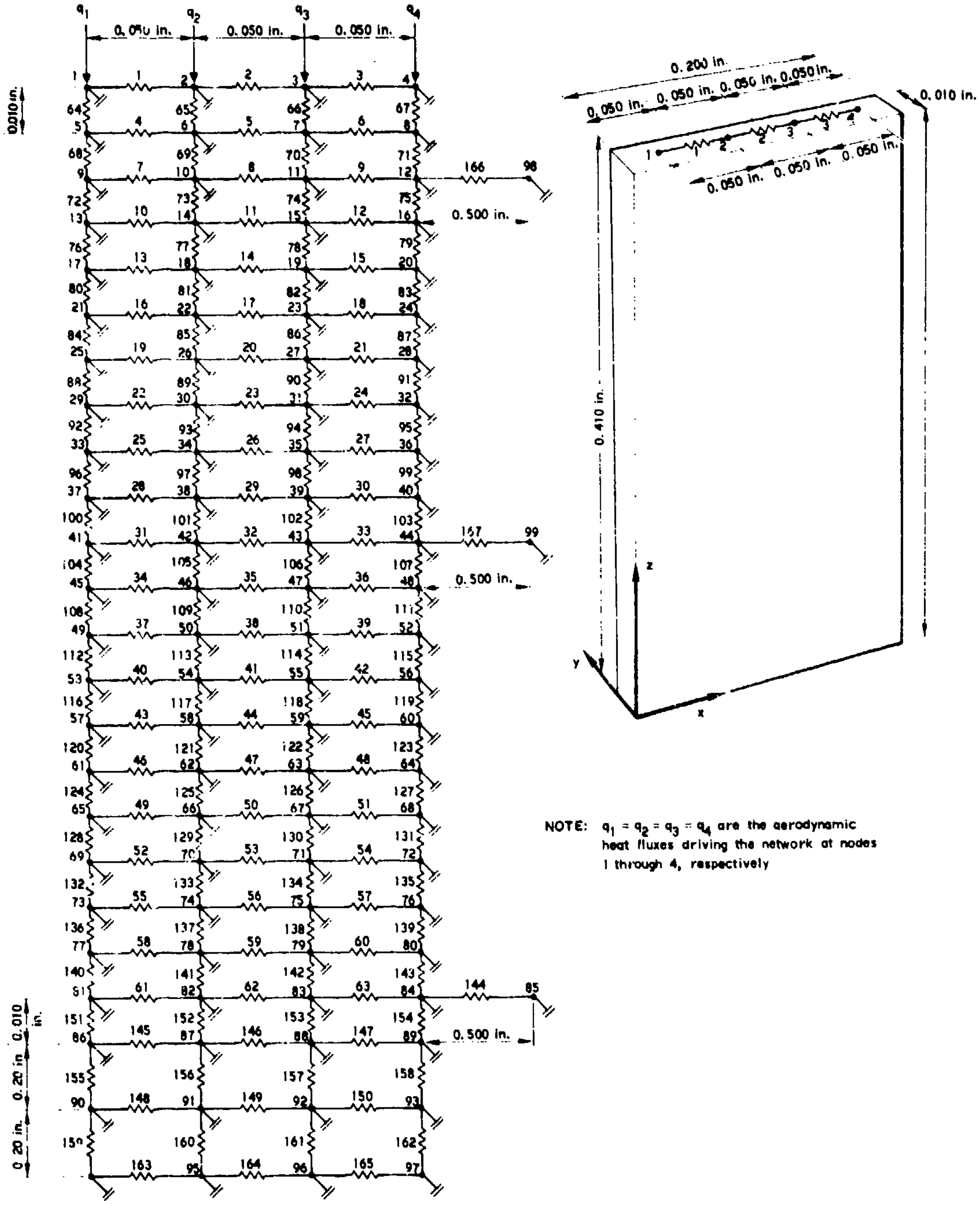

Fig. A-1 0.410 in. Long Multiwire Isothermal Thermocouple Plug Simulation trajectory. The term ascent heating is a misnomer, as this subroutine handles reentry heating as well.

The "uniquely numbered" elements of the Fig. A-1 simulation evolved in two stages, hence the discontinuity in the designation of the horizontal thermal resistances from numbers 63 through 145. The thermal resistance dimensions are summarized in Table A-1 per the reference coordinate system sketched on Fig. A-1. The analyst is able to set up the heat transfer areas and path lengths from Table A-1. Similarly, the dimensions of the thermal capacitances are presented in Table A-2. These dimensions permit the analyst to calculate the incremental volumes from which the thermal capacitors are calculated.

Each of the heatshield resistances, R, is calculated from the equation

$$R = \frac{\ell}{KA} \tag{A-1}$$

where

ℓ = heat transfer path length between nodes, ft

K = thermal conductivity of the heatshield material, Btu/sec-ft-°F

A = heat transfer area, sq ft

The thermal resistances, 7 to 9, 31 to 33, and 61 to 63 for the simulations of the 0.020, 0.100, and 0.200-in. finite slabs are the horizontal resistances of three materials in parallel. Therefore, each of these resistances is determined from

$$\frac{1}{R} = \frac{1}{R_{Heatshield}} + \frac{1}{R_{Insulation}} + \frac{1}{R_{Wire}} \tag{A-2}$$

Table A-1 Thermal Resistances Summary

Resistance No.	Dimensions, in.			Material	Type	Remarks
	x-axis	y-axis	z-axis			
1-63	0.050	0.010	0.010	Heatshield	Horizontal	
145-147	0.050	0.010	0.015	Heatshield	Horizontal	
148-165	0.050	0.010	0.020	Heatshield	Horizontal	
64-143	0.050	0.010	0.010	Heatshield	Vertical	
151-154	0.050	0.010	0.015	Heatshield	Vertical	
155-162	0.050	0.010	0.020	Heatshield	Vertical	
7-9	0.050	0.010	0.010	Heatshield, insulation and wire	Horizontal	0.020 in. long plugs only
31-33	0.050	0.010	0.010	Heatshield, insulation and wire	Horizontal	0.100 in. long plugs only
61-63	0.050	0.010	0.010	Heatshield, insulation and wire	Horizontal	0.200 in. long plugs only
144, 166 167	Insulated wire where insulation thickness and wire diameter and length varied.					

Note: Fig. A-1 depicts the 0.410 in. long multiwire isothermal thermocouple plug only in which no allowance was made for heat transfer in the x-direction through the thermocouple wire and its insulation. This x-direction heat transfer was accounted for in the simulation of the 0.020, 0.100, and 0.200 in. finite thickness plugs only.

Note: The y-axis dimension varies as a function of the simulation model per Fig. 6, where the y-axis dimension is equal to width, w, of Fig. 6.

Table A-2 Thermal Capacitances Summary

Capacitance No.	Dimensions, in.			Material
	x-axis	y-axis	z-axis	
1-4	0.050	0.010	0.005	Heatshield
5-8	0.050	0.010	0.010	Heatshield
9-12	0.050			Heatshield, wire, and insulation
13-40	0.050	0.010	0.010	Heatshield
41-44	0.050	0.010		Heatshield, wire, and insulation
45-80	0.500	0.010	0.010	Heatshield
81-84	0.050			Heatshield, wire, and insulation
98, 99 & 85			0.500	Wire
86-89	0.050	0.010	0.105	Heatshield
90-93	0.050	0.010	0.200	Heatshield
94-97	0.050	0.010	0.100	Heatshield

Each of the heatshield capacitances, C, is calculated from the equation

$$C = \rho V C_p \tag{A-3}$$

where

ρ = material density, pcf

V = incremental volume, cu ft

C_p = specific heat, Btu/lb-°F

The thermal capacitances, 9 to 12, 41 to 44, and 81 to 84 are comprised of three materials. Therefore, these thermal capacitances are determined from

$$C = C_{Heatshield} + C_{Wire} + C_{Insulation} \tag{A-4}$$

The material thermodynamic properties are tabulated in Tables A-3, A-4, and A-5 for the thermocouple wire, insulation, and virgin plastic heatshield materials, respectively. The effe[illegible] of the heatshield thermodynamic properties are discussed in detail in Appendix B.

Table A-3 Thermodynamic Properties of Tungsten/ Rhenium Thermocouples

T, °F	K_{Re5}, Btu/hr-ft-°F	K_{Re5}, Btu/sec-ft-°F	K_{Re26}, Btu/hr-ft-°F	K_{Re26}, Btu/sec-ft-°F	K_W, Btu/hr-ft-°F	K_W, Btu/sec-ft-°F
100	88	0.0244	77	0.0214	92	0.0256
1000	70	0.0195	62	0.0173	73	0.0202
2000	63	0.0175	58	0.0161	64	0.0178
3000	62	0.0172	57	0.0158	60	0.0167

ρ(Re5) = 0.701 lb/cu in. = 1210 lb/cu ft

ρ(Re26) = 0.714 lb/cu in. = 1230 lb/cu ft

T, °C	T, °F	C_p(W), Btu/lb-°F	C_p(Re26), Btu/lb-°F	C_p(Re) Btu/lb-°F
20	68	0.032		
27	79.6		0.0335	0.035
400	752	0.036		0.058
500	932		0.0345	0.061
1000	1832	0.040	0.0374	0.075
1500	2732	0.045	0.0400	0.0805
2000	3632		0.0436	0.086
2500	4532		0.0456	0.092

ρ = density, lb/cu ft

C_p = specific heat, Btu/lb-°F

K = thermal conductivity, Btu/sec-ft-°F

T = temperature, °F

Re5, 5 percent rhenium - 95 percent tungsten by weight wire

Re26, 26 percent rhenium - 74 percent tungsten by weight wire

W, 100 percent tungsten by weight wire

Re, 100 percent rhenium by weight wire

Table A-4 Thermodynamic Properties of the BPN Insulation Material

Material	K, Btu/sec-ft-°F	C_p, Btu/lb-°F	ρ, lb/cu ft	Remarks
BPN	0.0236	0.2	125	$\overrightarrow{A}$ - direction for vapor deposited
	0.0055			Hot pressed
	0.000266			C - direction ↓ for vapor deposited

Note: The BPN thermoconductivity is highly dependent on the fabrication technique and the direction of heat transfer for the vapor deposited BPN.

Table A-5 Virgin Plastic Heatshield Thermodynamic Properties

Carbon phenolic (ρ = 90.4 lb/cu ft)

Temperature, °R	460	660	860	1060	2000	3000
K, Btu/sec-ft-°R	0.0000874	0.00012	0.000124	0.00013	0.000201	0.000340
C_p, Btu/lb-°R	0.235	0.31	0.352	0.547	1.07	1.4

Tape wrapped quartz phenolic (ρ = 109 lb/cu ft)

Temperature, °R	460	960	1460	1960	2460
K, Btu/sec-ft-°R	0.00005	0.000075	0.000065	0.000075	0.000085
C_p, Btu/lb-°R	0.21	0.30	0.36	0.37	0.385

APPENDIX B

As mentioned in the Analysis Model section of this study, the varying of the heatshield specific heat, thermal conductivity, and density to account for the ablative process may cause significant errors in the calculated temperatures for temperatures exceeding 1000°F. Even the selection of these properties as a function of heatshield temperature for the Charring Ablator computer program [5] depends on the procedure used to obtain them and on the application in which they are used [12, 13]. As discussed in [12, 13], the thermal conductivity of a carbon phenolic char at 2500°F may be obtained, for example, from a piece of carbon phenolic that has been precharred in an oven and held at 2500°F while its thermal conductivity is derived from temperature measurements in a guarded heat flow meter under steady state conditions. Unfortunately, this steady state carbon phenolic char thermoconductivity may not agree with that of a 2500°F char on a reentry vehicle subjected to the severe transient aerodynamic heating environment with its attendant ablation processes. The [12, 13] steady state derived carbon phenolic char thermal conductivity may differ from the actual encountered, in flight by several factors. The entire subject of carbon phenolic char properties as derived in the laboratory as compared to those expected in flight are discussed in detail in [13]. The consequences of the variations in carbon phenolic properties with temperature are summarized in Fig. B-1 where the temperature histories in a 0.410-in. carbon phenolic plug without thermocouple assemblies at depths of 0.020, 0.100, and 0.200 in.

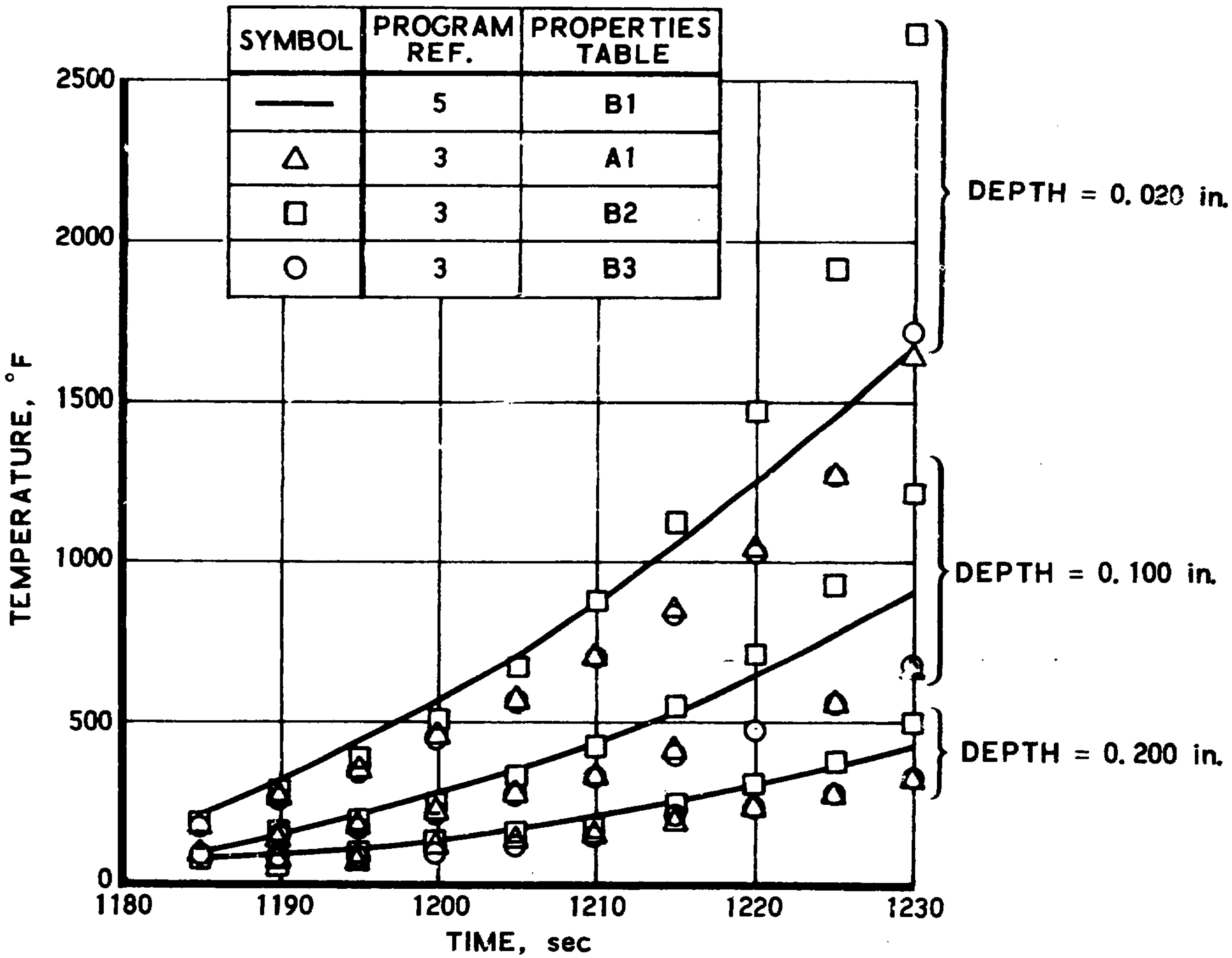

Fig. B-1 Carbon Phenolic Thermodynamic Properties' Effects on the Temperature History are presented for the carbon phenolic specific heats, thermoconductivities and densities presented in Tables A-1, B-1, B-2, and B-3.

The basic case [represented by the solid line] in the Fig. B-1 temperature histories are the ones obtained using the [5] char layer heating program with the Table B-1 carbon phenolic heatshield thermodynamic properties. This combination represents the current standard heatshield thermodynamic design tools for reentry vehicles.

The temperature histories based on the [3] computer program and the Table B-2 averaged carbon phenolic virgin plastic heatshield properties (represented on Fig. B-1 by the squares) compare quite favorably to those calculated with the [5] computer program for temperatures up to about 1100°F.

The temperature histories based on the [3] computer program and either the Table A-1 carbon phenolic virgin plastic (represented by the triangles on Fig. B-1) or the Table B-3 merged carbon phenolic (represented by circles on Fig. B-1) heatshield material thermodynamic properties did not match those calculated with the [5] computer program for temperatures between 250 and 1500°F. Therefore, the Table B-1 averaged properties were used in this study, but the accuracy of the temperature histories will decrease for temperatures in excess of 1100°F. As stated previously in the Analytical Model Section of this report, the results of this study should be regarded in a qualitative sense rather than a quantitative sense, expecially for temperatures in excess of 1100°F.

Table B-1 Carbon Phenolic Heatshield Properties

Virgin Plastic, ρ = 90.4 lb/cu ft

Temperature, °R	K, Btu/sec-ft-°R	C_p, Btu/lb-°R
460	0.0000874	0.235
660	0.00012	0.31
860	0.000124	0.352
1060	0.00013	0.547
2000	0.000201	1.07
3000	0.000340	1.4

Char, ρ = 74 16/cu ft

Temperature, °R	K, Btu/sec-ft-°R	C_p, Btu/lb-°R
860	0.000101	0.0602
1060	0.000105	0.0794
2000	0.000162	0.274
3000	0.000214	0.341
4000	0.000275	0.3715
5000	0.000333	0.384
6000	0.000389	0.40

Table B-2 Averaged Carbon Phenolic Virgin Plastic Heatshield Properties

ρ = 90 lb/cu ft
K = 0.00012 Btu/sec-ft-°R
C_p = 0.31 Btu/lb-°R

Table B-3 Merged Carbon Phenolic Heatshield Properties

Temperature °F	K Btu/sec-ft-°R	C_p Btu/lb-°F	ρ lb/cu ft
0	0.0000874	0.235	90.4
200	0.000112	0.31	90.4
400	0.00012	0.352	90.4
600	0.000124	0.547	90.4
1540	0.000195	1.07	90.4
2540	0.000214	0.341	74
3540	0.000275	0.3715	74
4540	0.000333	0.384	74
5540	0.000389	0.40	74

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